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## Investigation of routing optimization schemes for future all-IP dynamic access network structures

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# Investigation of Routing Optimization Schemes for Future All-IP Dynamic Access Network Structures

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King's College London



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## Abstract

Over the course of the last few decades, Internet has evolved to form a major technological component in our society. Accompanying this exponential growth are many challenges embracing both users expectations and ambitions of network providers. Internet Protocol (IP) is continuously being extended from the native Internet towards ubiquitous packet delivery models for the next generation of cellular networks. The two families of networks with their means of access, technologies and architectures are converging.

The mutable access network structures, deployment practicalities and global traffic increase, necessitate advancements of packet delivery models. Evolution of the cellular network architectures introduces the flat-IP structure and novel topological arrangements in the backhaul. A flexible routing within an efficient Traffic Engineering (TE) is needed for novel random all-IP access network topologies with heterogeneous wireless accesses. These requirements converge with the conventional IP intra-domain routing concepts. Multi-Plane Routing (MPR) is a TE approach comprised of offline and online features tailored for all-IP access networks. Diversity is leveraged upon via multiple paths between traffic sources and destinations rendered by slicing the physical topology into multiple logical routing planes. Performance is enhanced utilising the entire topology while minimising the MPR-incurred protocol overhead.

In this thesis, MPR extensions reflecting the evolution of access networks and emerging traffic types are studied. Minimum Set Cover (MSC) mathematical approach for random graphs representations of IP access network is applied accommodating novel features in offline TE: capacity planning/projections in conjunction with path correlations. Initially, a MPR utilization of the whole topology is validated via extensive simulations for diverse models of IP packet delivery improving upon key performance criteria and supporting meshing. The study proceeds to broader cases of random topologies of different sizes and sparseness where MSC-approach proves as superior by managing such complex routing resources. Additionally, Quality of Service (QoS) is tested for many traffic types including the Tactile traffic with its stringent requirements.

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# List of publications

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## Conferences:

1. B. Abrishamchi, M. Farhoudi, A. Mihailovic and A.H. Aghvami, "A Novel Minimum Set Cover Routing Plane Construction Approach for Random Wireless IP Access Networks" IEEE Wireless Communications and Networking Conference (WCNC), pp. 1-6, Barcelona, 15-18 Apr. 2018.
2. M. Farhoudi, P. Palantas, B. Abrishamchi, A. Mihailovic and A.H. Aghvami, "A Novel Reliable Routing Scheme for Tactile-oriented Internet Traffic," International Conference on Telecommunications (ICT), pp. 1044-1047, Limasol, 3-5 May 2017.
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# List of abbreviations

AR	Aggregation Router
AS	Autonomous System
BGP	Border Gateway Protocol
DiffServ	Differentiated Services
ECMP	Equal Cost Multipath
eNodeB	Evolved Node B
FIB	Forwarding Information Base
GDP	Growth Domestic Product
GW	Gateway
H2H	Human to Machine
IETF	Internet Engineering Task Force
IGP	Interior Gateway Protocol
INP	Internet Network Provider
IntServ	Integrated Services
IP	Internet Protocol
IS-IS	Intermediate System to Intermediate System
ISP	Internet Service Providers
ITU	International Telecommunication Union
LSP	Label Switched Path
LTE	Long-Term Evolution
M2M	Machine to Machine
MLU	Maximum Link Utilisation
MPLS	Multi-Protocol Label Switching
MPR	Multi-Plane Routing
MSC	Minimum Set Cover

MT-OSPF	Multi-Topology OSPF
NFV	Network Function Virtualization
OSPF	Open Shortest Path First
PDI	Path Diversity Index
QMPR	QoS-aware Multi-Plane Routing
QMSC	QoS-aware Minimum-Set Cover
QoS	Quality of Service
RIB	Routing Information Base
RP	Routing Plane
RSVP	Resource Reservation Protocol
SDN	Software-Defined Networking
SLR	Service Level Requirement
TCP	Transmission Control Protocol
TE	Traffic Engineering
TM	Traffic Matrix
ToS	Type of Service
VoIP	Voice Over IP

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# 1

## Introduction

The internet network started life as a local platform with limited interactions and a globally connected network vision. Ever since, Internet has evolved to become an open global platform with a widespread information infrastructure, that would enable everyone, everywhere to share information, access wide ranging materials, and redefine geographic and cultural boundaries. Internet's growth has transformed it into a multi-faceted environment connecting users on a global scale. Correspondingly, this growth has significantly impacted our daily interactions. The Internet's routing fabric is currently confronted by a traffic management challenge with the emergence of highly demanding applications and the surfacing of new devices in recent years. Massive growth of advanced multimedia applications which contribute greatly to the surging mobile and Wi-Fi traffic has been enabled through the evolution of cellular network generation connectivity (2G, all the way to 4G/LTE - LTE advanced and 5G). It is expected that by 2021, there will be 1.5 mobile devices per capita (8.3 billion personal mobile-ready devices) and mobile data traffic will reach new milestones. There will also exist around 3.3 billion M2M connections by 2021 [1]. Meanwhile, networks especially cellular/mobile are moving towards denser access, which indicates more meshing, access points and increased randomness.

In order to cope with the rising traffic demands, network providers have resorted to over-

provisioning as a solution for a smoother traffic management. However, despite the significant and continuous rise in the bandwidth volume throughout the Internet, it is becoming increasingly difficult to cope with the rising traffic demands by simply over-provisioning. Internet has been best-effort for long. The rise of traffic types with increasingly strict Quality of Service (QoS) characteristics throughout the Internet calls for a shift from a best-effort model to a QoS differentiation-based model in some scenarios, especially at the edges where access networks are deployed. The need for such a transition is further underscored by the the rapid rise in continuous media streaming applications along with the introduction of new traffic applications namely Haptic communication. In addition, the increasing number of active users with demanding devices contributing to highly demanding applications and increased mobility at network edges is shifting the focus from core to access.

The increasingly dense and heterogeneous access environment has motivated the need for new considerations and adaptations in the structural setup along with enforcement of new interfaces in order to conform to the recent transformations and satisfy the gigabit-level data traffic. Correspondingly, as the nature of Internet has evolved, there have been consistent adjustments in the architectural and structural setup of access networks that need to be matched with new considerations in the structural setup.

Consequently, the evolution of Internet networks in line with the increasing traffic volume and real-time applications along with new considerations in structural setup and architectural layout necessitate consistent adaptations in the networking aspects namely topologies and routing optimization methods.

## **1.1 The Evolution of All-IP Access Networks**

The access network was originally designed to carry no more than voice at a strictly limited bandwidth. Ever since, access networks have evolved to carry a far wider and more diverse range of services and increasingly variant traffic types such as data, video, voice, mobile TV



and forthcoming traffic types associated with Tactile applications. This growing demand is certainly far more than the original network designers would have ever envisaged feasible. Therefore, this demand presents a challenge for network operators that need to satisfy users' expected constant quality delivery (extending from core to access, matching the augmentation of devices' capabilities) in consideration of the rising number of network devices and contending data traffic (QoS) with the backdrop of limited bandwidth. In view of these new expectations, multi-path diversity in IP networks has been considered to accommodate for the needs of the future access networks.

Access networks can be defined as bounded transitional scoped administrative domains that facilitate access to terminals through access nodes, internal communication between access nodes and access towards the Internet through the aggregate Gateway. Access networks have evolved in consistent with transformations in networking protocols aligned with the developing 5G concepts. Meanwhile, the telecom world is moving towards an all-IP network architecture, as IP is the dominant internetworking protocol in operation today. To this end, emerging access networks can utilize the ubiquitous IP infrastructure [2, 3].

Early cellular networks were initially implemented such that very limited IP routing capabilities would be supported. Correspondingly, access networks' concepts were originally developed in association with solely Internet access networks (i.e. campus environments or ISP providers with wired or wireless access). Subsequently, IP access network architectures were envisaged at the time of early generation cellular access technologies [4] together with their associated packet forwarding functionalists [5]. Thenceforth, cellular and IP networks have increasingly converged at the edges of networks to represent IP access networks. This convergence \* would translate into an extended adoption of native IP protocols extending from core to access networks, hence facilitating a more uniform network wide communication [6]. Correspondingly, with the expected surge in the global IP traffic aligned with the rapid rise in

---

\*It seems that the biggest obstacle to full convergence of IP network layer transport is surprisingly its major benefits in global endorsements. Cellular/mobile networks need more diversity and control not appropriately provided by best-effort and shortest-path properties of the native IP routing.

IP-based applications combined with faster radio access technologies throughout the Internet; there has been an adoption of open IP interfaces in the integrated evolutionary backhaul network designs [7, 8]. This is an indication of the cellular wired backhaul and Internet access based network designs converging on the IP-based infrastructure model. Henceforth, this design space will be referred to as all-IP access networks which are located at the edges of the Internet routing fabric.

It is envisioned that access networks with structural properties that are in consistent with the heterogeneous-oriented limited capacity models pertaining to macro-, femto- and micro-cell access points will emerge. Therefore, it is easy to imagine the opportunities for highly adaptable deployment of IP access networks via rollouts and networking of wireless access points with technologies such as WiFi, femtocells and macrocells solutions. The expected trends towards heterogeneous access network structures could also have a significant impact on the deployment of evolutionary access networks.

Moreover, the unpredictable nature of future access network structures necessitates consistent adaptations by network providers to enable disruption and loss free networks supported with the developing IP infrastructure. Correspondingly, randomly shaped network structures (i.e. random graphs) must also be taken into consideration as a significant element to accommodate for the emerging all-IP access network structures.

## **1.2 Challenges and Objectives**

The demand from sharply growing customer traffic over the global Internet, changing dynamics in Internet traffic and increased network density have put a burden on Internet Network Providers (INPs). INPs would need to meet the users' demands with various QoS requirements who expect a quality service delivery across both wireless and wired networks. Traffic engineering is considered as an important mechanism for Internet network providers seeking to optimize network performance and traffic delivery. Routing optimization plays a key role in

traffic engineering, finding efficient routes so as to achieve the desired network performance. In this thesis, we are concerned with intradomain TE, which includes both MPLS- and IP-based routing optimization methods as the two main categories of solutions.

The concept of traffic engineering was first introduced in MPLS-based environments [9]. MPLS is still widely deployed in access networks where encapsulated IP packets are delivered over Labelled Switched Paths (LSPs) (a solution that works on "top" of native IP suite). Explicit routing and arbitrary splitting of traffic are enabled through MPLS based on which the complexity and overhead associated with building and maintaining LSPs give rise to scalability, robustness issues and the extra information added to each packet [9].

On the other hand, native IP solutions such as Open Shortest Path First (OSPF) [10] which is a widely adopted Interior Gateway Protocol (intra-domain) dynamic link-state IP protocol are used to distribute IP routing information throughout a single Autonomous System (AS). OSPF is scalable and robust against element failures but does not support arbitrary traffic splitting as opposed to MPLS. In addition, OSPF does not intrinsically facilitate efficient path diversity as path alterations could be timely due to the required update of link weights and retransmission of the corresponding changes across the network enabled through Link State Advertisements (LSAs) despite of performance optimization efforts.

Equal-Cost Multi-Path (ECMP) [11] which is an add-on option of OSPF was initially adopted and evaluated in [12]. ECMP aims to tune the link weights facilitating equal multi-path traffic splitting in order to achieve load balancing that would rival MPLS networks. The weight tuning makes OSPF and ECMP slow to converge and highly intractable respectively in case of large and random topologies specially for numerous number of sources and destinations [13]. Even the best setting of the weights can diverge considerably from optimal as discussed in [13, 14]. Moreover, the equal splitting of traffic is not sufficient for near-optimal performance as compared with MPLS since optimal routing would generally require arbitrary splitting of traffic [9]. It is notable that MPLS is still widely used while there is significant ongoing research invested on enhancing the MPLS and IP routing mechanisms, which means

that the current solutions that are practically in place are not optimal nor satisfactory for the reasons briefly elaborated on above. SDN/NFV represents another approach that works by breaking down the abstractions that form the foundations of traditional networks, while aiming to essentially improve the same efficiencies.

The significant spike in Internet traffic types (namely Tactile) with some strict QoS metrics' associations represents a major challenge in future all-IP access networks and requires the adaptation of some QoS-aware policies accordingly. In addition, more innovative approaches might be required to be integrated in order to address the specific stringent requirements associated with some traffic types. Tactile applications exemplify the aforementioned stringent traffic types and research in the field of future scoped wired and wireless access networks has been recognized as being essential for Tactile Internet [15].

Moreover, the architectural evolution of access networks demands consistent adaptations to routing optimization methods within such domains. Traffic distribution break down model represents another significant element to be considered in future access networks considering the surge in traffic locality with the outgoing/external traffic still being highly existent. Therefore, the routing optimization techniques must take into account the fluctuating traffic locality balance in order to render a viable solution.

Multi-plane Routing (MPR) is a purely IP-based solution and was initially introduced in [16]. MPR which integrates multiple instances of OSPF paths in its approach to facilitate path diversity, aims to address the deficiencies associated with MPLS and ECMP and present a comprehensive solution for routing in future all-IP access networks. A study has recently emerged containing the analysis of practical aspects of MPR in extensive simulations for limited pre-defined tree-like topologies [17]. MPR is discussed and presented in further detail in section 2.3.2. In this research, MPR is used as basis methodology to which enhancements and modifications are applied in consistent with the practical aspects briefly discussed above and throughout this thesis with the aim of presenting more of a viable solution in future access networks.

Meanwhile, the unpredictable nature of future access network structures calls for network providers to adapt accordingly in order to facilitate loss free networks supported with the developing IP infrastructure. This would require the extensive test for suitability of the proposed routing optimization approaches in randomly shaped access networks (random graphs). In other words, in order to enable a generally applicable approach in future access network structures, it is essential for MPR's application in networks of random nature (random graphs) to be studied. MPR's applicability and performance superiority's verification in case of random networks can further justify MPR as a practical routing optimization approach in future access networks. Moreover, given the trend towards heterogeneous architectures and the associated rising traffic volume, MPR's application with integrated diversity under a heterogeneous environment seems increasingly relevant.

## 1.3 Thesis Contributions

Techniques for optimisation of routing performances for future all-IP access networks that have been developed and extensively investigated are now facing the latest 5G features and insights. Key routing optimization challenges within the novel network structures underlining this thesis state of the art contributions were presented in the preceding subsection. Firstly, MPRs extensions are developed through the considerations and insights into various pertinent practical aspects in the architectural evolution of access networks and the needs that accompany the surfacing of new traffic applications. Subsequently, a MSC-based traffic engineering mechanism for randomly generated networks (i.e. random graphs) is proposed and investigated extensively in terms of both offline and online perspectives. The contributions of this thesis are laid out as follows. It is noted that each chapter provides a more detailed outline of its contributions:

- A comprehensive, novel and practically-founded performance evaluation of multi-plane routing via MPR is conducted. The novel scenarios used for validations contain the

emerging practicalities of access network dynamics and structures and reflect multitudes of performance criteria. Hence, the MPR analysis initially contained in [18] and [19] that dealt with a single topology and simple traffic flows (only distributed from the networks Gateway (GW)) respectively, is extended further to reveal very relevant specifics of how access networks would operate and disseminate the traffic: a) two Cases (I and II) of traffic flow distributions: to/from the outside Internet, and, internally inside the access network between its nodes; b) extended number of topologies and their meshing configurations; and, c) random allocations of Ingress and Egress points of traffic to include almost any entity in the access network with observations broadened towards both uplink and downlink traffic flows. The study appropriately meets the evolution and convergences of cellular and Internet networks, endorsement of flat-IP models of communications and interfacing between edge nodes. Furthermore, a dedicated study is conducted including the novel traffic type, that is, tactile traffic. To support this traffic a specific policy is applied in order to meet the stringent traffic requirements of the Tactile/haptic communications further confirming the suitability of multi-plane routing.

- Complexities of topologies and meshing configurations coupled with multi-plane routing are matched to a well known mathematical problem, Minimum Set Cover (MSC). The primary offline algorithms objective of multiple RP construction is proven as a generalization of the MSC problem which is NP-complete and hence justifies the adaptation of heuristics. The mathematical foundation is then taken further to extend the solutions scope to more complex and larger random graphs, i.e. random access network topologies with extensive number of nodes, links, multiple GWs and capacities (following the increasingly heterogeneous nature of the emerging access networks capacities [20]) etc. In these more extreme cases of topologies, MPRs offline TE method falls short of rendering viable sets of multiple planes. The novel TE based on MSC-based routing optimisation is accordingly formulated via the new offline algorithm that considers large, random topological configurations and applies novel tools for explicit inclusion of link capaci-

ties and path correlations in constructing RPs. This approach radically differs from the previous MPR offline method, which is more implicit and based on manipulations of link weights. Thus, a plane-set chosen for a random topology prior to the online traffic injections minimizes projected residual capacities and overlaps of Ingress-Egress paths, hence maximises the use of routing resources in access networks. This problem significantly scales up since RPs become large and more complex in random graphs; hence, appropriate tree-based algorithms are adapted for the purpose of the offline finite full set RPs constructions. Finally, a dynamic MSC-based cost function assesses this process of constructing diverse sets of RPs in random access networks and provides the final step for the novel comprehensive dynamic MSC-based RP construction algorithm. A thorough performance analysis is conducted of both offline and online features of MSC which compares and affirms the functional ability of the MSC-based approach and its QoS enabled extension (i.e. QMSC) in diverse, large and complex random topologies against its rival strategies namely OSPF, InvCap and MPLS.

## 1.4 Thesis Organisation

A chapter-by-chapter outline and description of the thesis including the major contributions of each chapter is presented as follows:

In chapter 2, the fundamentals and literature review are presented. This chapter aims to provide an elaborative background study and related work with regards to the different aspects covered in this thesis.

Chapter 3 presents practical aspects of MPR's application in future all-IP access networks. To this end, IP TE-based MPR has been modified and remodelled in case of both offline and online TE approaches. Furthermore, Tactile Internet with its strict reliable communications criteria is studied and a novel reliable MPR-based routing approach is proposed accordingly.

A novel MSC-based paths-diverse offline TE algorithm which is comprehensively appli-

cable to randomly shaped access network structures is proposed in Chapter 4. The proposed approach is in line with the mutable structural nature of future dense heterogeneous access networks.

In chapter 5, our proposed MSC-based approach is investigated in terms of various online performance metrics and compared against rival TE strategies. This chapter extends and complements its preceding chapter by introducing an online traffic model. To this end, a comprehensive multi-topology MSC Link-State Routing Approach for emerging random all-IP access network topologies is put forward.

The last chapter presents the conclusions of the thesis and encompasses a brief discussion on topics for future research.



## 2

# Fundamentals and Literature Review

## 2.1 Traffic Engineering Classifications

Presently, Internet is still best-effort. Therefore, IP Network Providers (INPs) have increasingly adopted bandwidth over-provisioning strategy with the introduction of high speed links across the real implementation of Traffic Engineering (TE) schemes. A fundamental classification of conventional unicast TE approaches that have been numerous proposed in the literature is initially presented in an extensive survey [9]: a) intra- vs. inter-domain, b) MPLS- vs IP-based, and, c) offline vs. online. Such a classification still remains the placeholder for understanding the main differences between TE schemes and continues to be relevant in real implementations of routing, somewhat reflecting that behind the enormous efforts in devising new TE schemes there is still the unfulfilled pursuit for an optimal solution. From the practical point of view, lack of optimal TE solution(s) or a global consensus often simply results in INPs continuing to opt out to the over-provisioning strategy for handling the unpredictable traffic demands and pragmatic configurations of networks (e.g. topologies).

Correspondingly, the fast rising number of new devices that are associated with growing real-time applications over the Internet demands consistent transformations in the routing optimization methodologies supporting these applications. Hence, it is increasingly becoming

essential for INPs and cellular network operators to adopt Traffic Engineering (TE) as an indispensable tool in managing networks' resources to meet rapid growth of the network and increasing demands coming from end users and new applications on both inter- and intra-domain scales [9, 21].

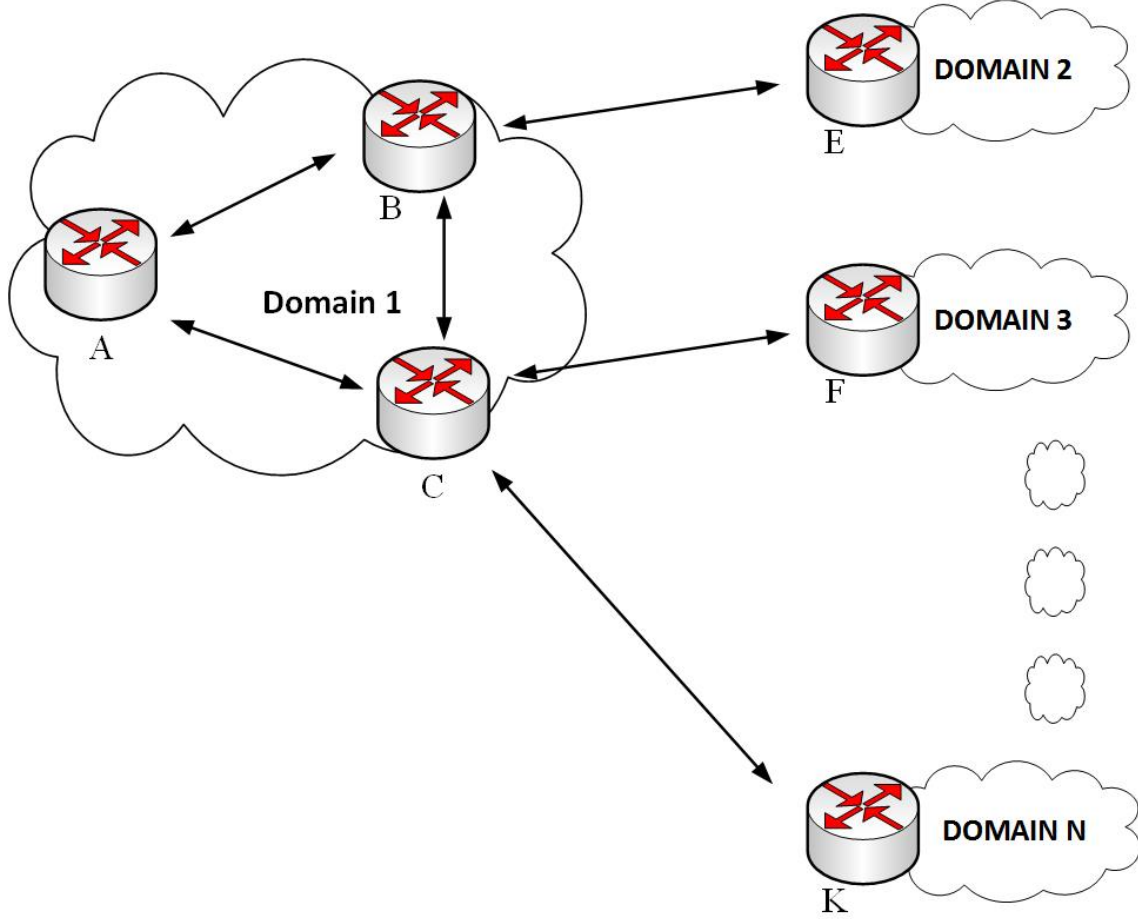
In a nutshell, TE corresponds to a routing optimization technique with the goal of improved network wide load balancing. Meanwhile, Quality of Service (QoS) and resilience are increasingly being considered in TE [9] as a set of features that differentiate performance enhancements from the general routing optimisation goals and focusing on specific network and traffic delivery performance criteria. Such considerations are justified by the new traffic types and applications demanding increasing QoS guarantees for performance criteria such as: jitter, packet loss, and end-to-end delay. In addition, a diverse range of objective functions consisting of combinations of extracted or combined conventional network performance criteria such as delay and throughput etc. have been adapted as a valuable tool for meeting the TE requirements. In fact, an early and relevant assessments of TE schemes applying a different angle in TE classifications, analyses such objective functions used in routing optimisations alongside the criteria that the functions aim to optimise: delay, throughput, cost, their combinations such as fairness, link utilisations etc., as surveyed in [22]. Generally, optimal TE is recently summarised as a solution that minimises a cost function under multi-commodity flow constraints [55] including some of the objective functions that either minimise maximum link utilisation (MLU), or, queuing delays, or, combinations of objective functions including user-utility and congestion control etc. A more detailed overview of the various solutions belonging to different categories of TE employed up to date will be presented in the following subsections alongside some reflections on the new network characteristics, paradigms in routing [23–26] and visions for devising new routing architectures and protocols.

### 2.1.1 Intra-domain TE vs. Inter-domain TE

From the foundational aspect of Internet traffic optimization scope, TE is divided into intra-domain and inter-domain which equally includes the MPLS- and naturally IP-based routing optimization methods [9]. As mentioned previously, in our research, we focus on intra-domain TE given that all-IP access networks are located at the edges of the Internet routing fabric. Intra-domain TE can be defined as a routing optimization approach between Autonomous System (AS) border routers (ASBRs) within one domain. Inter-domain TE is concerned with optimizing inter-domain traffic travelling across multiple ASs. In other words, inter-domain resource optimization can be defined as the optimal selection of ASBRs as the ingress/egress points for inter-domain traffic passing through the local AS. Figure 2.1 illustrates the difference between intra- and inter-domain TE semantics. In this example, the communications decision between ASBRs B/C and E/F/K as the egress points is the task of inter-domain/outbound TE. Meanwhile, intra-domain TE aims to identify an optimal internal path or multiple paths within each domain. It is notable that intra- and inter-domain TE should be considered concurrently in TE implementation given the network configuration and their consequent dependency on one another. Correspondingly, INPs must adapt both intra- and inter-domain TE in conjunction in order to meet the traffic engineering objectives [9]. While a similar structural differentiation of network domains could be drawn in parallel with architectures of early generations of cellular networks, focus on intra-domain routing nowadays equally applies to current and emerging generations of cellular (access) networks and the associated convergence of Internet and cellular network packet delivery methods [16, 17, 20].

### 2.1.2 IP TE vs. MPLS TE

In terms of the protocol tools for enforcing the routing instructions in routers, Intra-domain TE can be categorized into the MPLS (Multiprotocol Label Switching)- and IP-based TE. The concept of TE was actually first introduced in MPLS-based environments as a flow-based/virtual-circuit connection-oriented protocol [27–30], using explicit routing. MPLS is



**Figure 2.1:** Scope of traffic engineering. IntradomainTE considers optimized routing for each node pair within the network; On the other hand, interdomain TE focuses on optimized ASBR selection

still widely deployed in (cellular) access networks where encapsulated IP packets are delivered over Labelled Switched Paths (LSPs) calculated as optimal path(s) between a pair of traffic ingress/source and egress/destination. Explicit routing and arbitrary splitting of traffic are facilitated by MPLS and still guarantee more control and reliability during routing than the conventional best-effort Internet routing and most of the solutions for IP-based routing. However, it is well known that MPLS advantages, on the other hand, incur more complexity and overhead associated with building and maintaining LSPs and give rise to significant scalability and robustness issues along with the extra information added to each packet [9]. The overall number of LSPs (assuming full-mesh/connectivity) within an AS is  $O(N^2)$  where  $N$  is the number of ASBRs. This indicates a high LSPs provisioning overhead exacerbated in case

of large-scale networks. Additionally, provisioning back up LSPs is vital in case of MPLS TE as traffic would not be intrinsically re-routed in case of failures in contrast with IP-based TE. These shortcomings of MPLS, still remain the reasons for pursuing more efficient routing alternatives in some recent proposals.

Rather than installing an extra sub-layer of features as needed for running MPLS TE, IP-based TE generally augment the native, best effort network layer IP routing using cheaper protocol add-ons. Authors in [31–33] initially put forward the concept of IP-based TE (sometimes generically termed as destination-based TE [63]). Such IP-based TE is implemented through the link weights tuning in case of Interior Gateway Protocols (IGPs) such as Open Shortest Path First (OSPF) and Intermediate System - Intermediate System (ISIS) protocol [34] which are the commonly used intra-domain routing dynamic link-state IP protocols (i.e. IGPs). The manipulation of link weights were done in accordance with the given network topology and traffic demand in order to control intra-domain traffic and meet routing optimization objectives.

In contrast to MPLS TE, IP-based TE does not inherently enable explicit routing and arbitrary splitting of traffic since it is based on the shortest-path hop-by-hop routing principle (hence lacking flexibility in path selection) with relatively slow paths recalculation, burdening of all routers in the network with link weight calculations [35] and sacrificing optimality [36]. However, IP-based TE renders better scalability and availability as compared to MPLS-based TE since no overhead is associated with the path setups. Moreover, traffic is automatically rerouted via other available shortest paths in case of node/link failures as an integrated solution of IP-based TE without requiring explicitly provisioned backup paths (i.e. MPLS TE). Nonetheless, such auto-rerouting could lead to traffic distribution imbalance even across multiple domains (thus introducing new traffic congestion) in case of IP-based TE. Although challenging, finding solutions for optimal routing via IP-based TE is still highly relevant and a timely topic [37].

More outlook and analysis of existing MPLS and IP-based routing solutions are further presented in the remainder of this section, e.g. subsections 2.3.

### 2.1.3 Offline TE vs. Online TE

At the very advent of formulations of the principles for Internet TE [21], differentiations between offline and online TE provided an important aspect of the taxonomy. Essentially, the separation between the two types of TE solutions dealt with how routing plans (i.e. decisions on packet distributions in networks) are calculated. In simple terms, offline means that the computations need not be in real time, while online deals with adaptations of packet routes in response to real time situations typically in timescales of hours or sometimes minutes. The former can be computed prior to insertion of traffic into the network, or as an objective function of meeting routing performance criteria over a multidimensional solutions space of a given networks routing configuration and resources. Distinctions of offline and online TE methods was discussed at various levels of TE objectives and their functions, where online schemes functions are expected to minimise the probability of blocking future packet flow requests, while offline TE objectives attempt to minimise the load or the utilisation of the links, or, maximise available bandwidth [22]. A generic distinction between pre-traffic insertion and real time execution seems the most fitting definition and has been used to differentiate various classes of offline and online TE schemes that have emerged over time [9].

In MPLS, offline mode usually refers to methods that produce computationally optimal set of (e.g. shortest hop) paths that get transferred into LSPs by using a computer programming method or via cost functions that get transferred into hop counts (e.g. cost functions that include several QoS metrics [38]). As discussed in more details in subsection 2.3, offline methods for IP-based schemes include cases of equal cost paths rendering, smart planning of link weights for path calculations and use of multiple routing topologies.

In the case of online modes in MPLS, solutions can either perform on-demand recalculation of LSPs [24] or enforce dynamics splitting of traffic using variable splitting ratios [25]. Again, as discussed in more details in section 2.3, IP-based online schemes involve real-time readjustments of link weights, i.e. paths re-convergence.

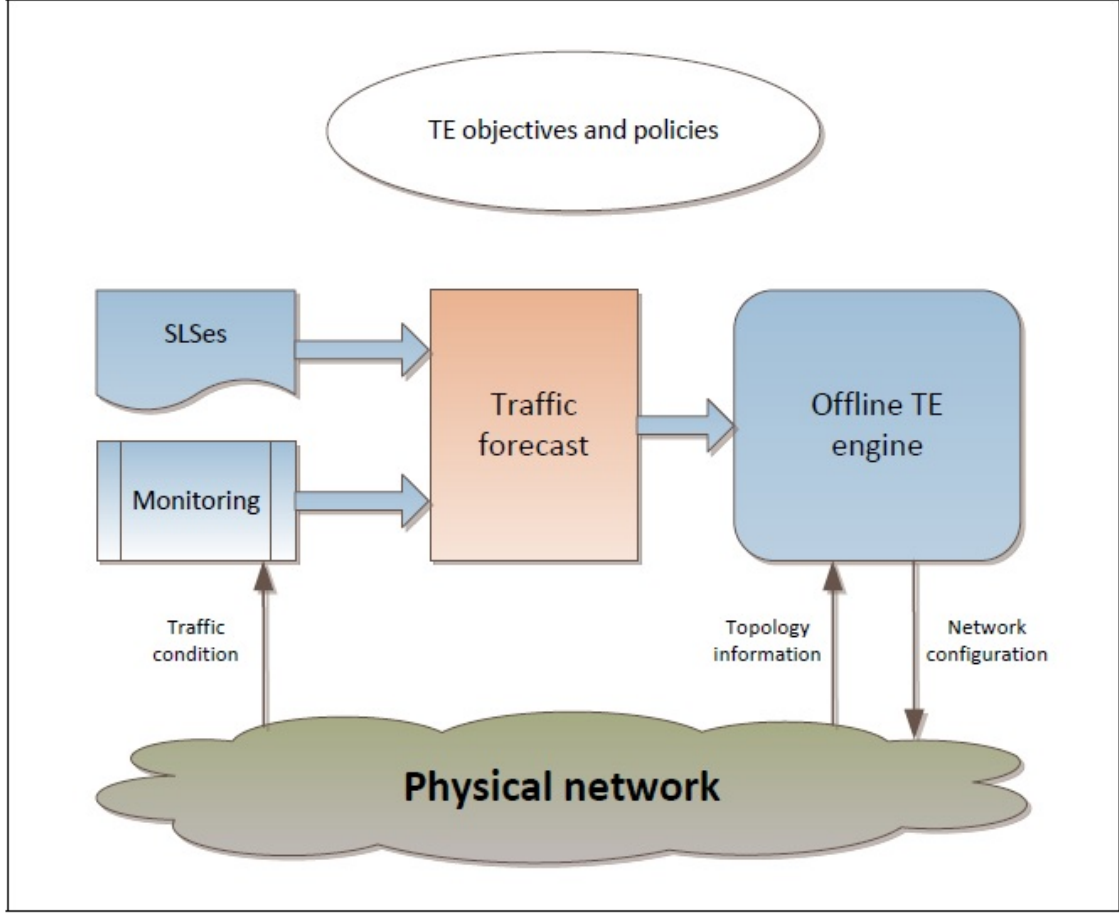
Away from the theoretical explanations and more in tune with how INPs manage the practi-

calities of network operations, classification into offline TE and online TE include the perspective of availability of traffic demands or timescale of operations. The principal factors setting apart the offline and online TE approaches are the availability of a Traffic Matrix (TM) and the time-frame of traffic management, i.e. in simple terms: can INPs predict traffic dynamics successfully. TM corresponds to the traffic volume between all pairs of sources and destinations in an IP AS under the control of an INP. In other terms, a TM embodies the overall bandwidth demand of all the individual traffic flows from an ingress/source to an egress/destination. Offline TE can be applied subsequent to the TM evaluation for a given network topology by an INP. Figure 2.2 illustrates the typical offline TE mechanism functionality. INPs can predict the TM \* in advance of routing optimization considering two main inputs: a monitoring/measurement and Service Level Specification (SLS) [39,40]. Considering that SLS is an agreement between the INP and customers, the INP can appraise the total bandwidth demand between each pair of ASBRs through augmenting every customers traffic predictions. Given the disconnection from traffic and network dynamics such as traffic bursts and failures, the Offline TE lacks the necessary traffic manipulation versatility. This characteristic renders the offline TE less effective standalone in view of the actual traffic patterns possible divergence from estimation. Meanwhile, Online TE standalone would struggle to manage future incoming traffic demand solely based on the current network state. Factors such as the deficiency of a global view of the traffic conditions usually cause such unpredictability of the incoming demands pattern.

In large dynamic network structures with dynamic traffic conditions in order to address the aforementioned issues associated with the offline and online TE mechanisms, while keeping the focus on maximising the routing resources, both online and offline mechanisms must be practically combined as complementary TE components. Hence, the INP can exert optimal control of the use of networks resources while being able to respond to variations of traffic within appropriate time scales. Therefore, offline TE should be applied as a behavioural guideline for

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\*Importance of offline algorithms have been extensively studied and applied typically assuming prior knowledge of traffic distributions in the network via input of traffic matrices [9]. MPR's offline algorithm does not assume a prior knowledge of the traffic dynamics hence prepares and balances the network for any occurrences.



**Figure 2.2:** offline TE mechanism

the more adaptive online TE which can handle the traffic dynamics which cannot be detected by the offline TE as recommended in the extensive survey in [9]. In this thesis, our proposed IP-based TE approaches feature both offline TE and online TE components concurrently.

## 2.2 All-IP Access Networks Emerging Challenges

Increased access density, heterogeneity, changes in the networks' traffic dynamics and the emergence of new traffic types have all influenced the design re-considerations of the current access structures and architectures. Correspondingly, it is becoming increasingly essential for access networks to adapt by becoming more application aware and dynamic. To this end, the structural setup and architectural interface of access networks need to be considered as such



networks are undergoing significant transformations in line with the developing 5G concepts and networking aspects.

With regards to the access topologies, meshed tree topologies constitute the most favoured for access networks given their simplicity and cost-effectiveness [41]. In addition, it is claimed that larger number of base stations and the corresponding increasing bandwidth demand from their radio access networks will inspire operators to forego the commonly used star based topology for a tree-topology [42]. Further justified by the rapid growth of more reliable and high bandwidth transmission technologies, the tree-based topologies are increasingly being favoured [41]. However, the changing nature of access network structures requires the extended consideration of randomly shaped structures for comprehensiveness of access networks' analysis. In conjunction, the increased density and heterogeneity in such structures is a significant factor to be considered. In the following subsections, significant emerging aspects that must be taken into consideration and addressed in the evolutionary all-IP access networks will be presented.

### **2.2.1 Emerging Convergence**

The Internet access based network and cellular wired backhaul are increasingly converging in the IP infrastructure model. Moreover, it is expected that 5G will enable fixed-mobile networking based on which fixed and mobile users will be catered for. Such a convergence will allow for the reassignment of the existing infrastructure [43].

There have been several propositions with regards to the next-generation IP networks' architectural and structural design layout. One of such propositions is the IP interconnection of base stations (i.e. flat user-plane architecture) where the control plane administers services<sup>†</sup>. Control is assigned to access nodes under such architectures. Authors in [44] discuss the strive and standardization challenges for flatter networks. The flat architecture has been considered in the Long-Term Evolution (LTE) and LTE advanced standardizations [45]. To this

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<sup>†</sup>The flat architecture corresponds to the horizontal trend in control and data plane flows marked by abolitions of core /access boundaries and packet level functionalities

end, the access and core networks are transitioning into a flat all-IP architecture. The number of functional network elements would be reduced with the adaption of flat-IP [45]. In Evolved Universal Terrestrial Radio Access (EUTRA), the radio and handover control responsibilities are distributed among base stations ( evolved Node B (eNodeB)) in flat architectures where eNodeBs are connected with direct logical interfaces [46]. Under flat architectures, traffic forwarding between neighbouring eNodeBs was to be enabled only briefly during handovers with traffic anchoring functionalities remaining centralized in the core network [47]. This would indicate the rare usage of the provisioned direct interfaces in backhaul environments.

With the potential advantages of the flat structure being materialized, it is expected for such architectures to enable improved latency and decreased network load [48]. In addition, traffic management and signalling support are to be facilitated by flat-IP

### **2.2.2 Traffic Distribution Model**

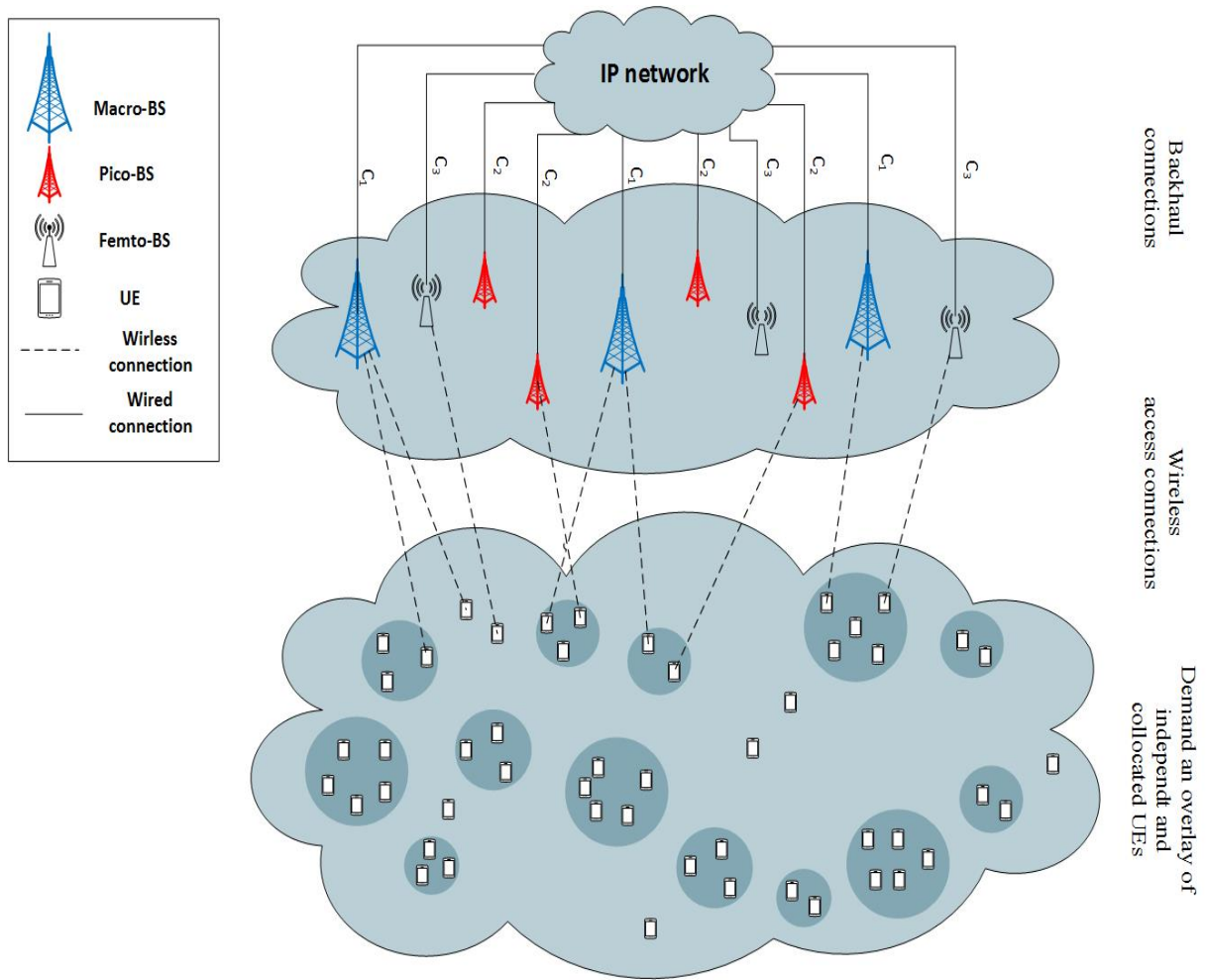
In view of the changing network architecture and the nature of traffic applications, traffic distribution model consideration is becoming increasingly necessary. Given the instance of an access network with a single aggregate gateway (representing several gateways) towards the Internet, local traffic corresponds to the internal communications within the access network (destined to an internal host), Similarly, the remote/external traffic can be defined as the traffic destined to an external Internet host. It is notable that with the increased popularity of applications such as YouTube, Netflix and mobile TV, remote traffic will continue representing a high proportion of traffic in access networks [49]. Meanwhile, the rising tendency towards latency-aware and topology-aware overlays contributes to the increase of traffic locality within the access network [50, 51]. Therefore, the Internet access aggregate gateway would still represent a traffic hot-spot with the backdrop of potential surge of traffic locality. The possible advantages of keeping traffic local in an access network to a possible extent was investigated in [35] while considering how the traffic demand is to be assigned to users in access networks. We should note that the traffic distribution model within every access network could be fundamentally dif-

ferent depending on factors such as user behaviours, the extent of localized communications, nature of the requested popular contents, together with some other unique characteristics that are associated with the access network.

Consequently, a thorough investigation of the future all-IP access networks must take into consideration the changing internal/external (local/remote) traffic distribution model.

### **2.2.3 Heterogeneity and Randomness**

Heterogeneous architectures and random network structures represent major issues that should be considered in the study of the future access networks. The general vision for 5G includes a converged heterogeneous network environment in which a variety of wired and wireless solutions are combined in order to interconnect a huge number of disparate end-devices and users [43]. The assumption of backhaul connections with unlimited capacity is very optimistic in the envisioned 5G HetHetNets [20]. To be more specific, the envisioned macro-, femto- and pico-cells will potentially have backhaul connections with constrained capacity. A sample three tier HetHetNet with macrocells, picocells, and femtocells, which have different associated backhaul capacities, is demonstrated in Figure 2.3 [20]. Additionally, in consideration of the uncertainties regarding the future all-IP access networks' structure and given the disparately shaped existing access network structures, consistent routing optimization techniques must be designed in order to be applicable to such random heterogeneous structures for the purpose of representing a comprehensive solution. Correspondingly, network engineering issue namely wireless access small cells installations in, for example, cities, high building etc., also contribute to great randomness and heterogeneity.



**Figure 2.3:** Emerging Access Network Structures, a sample three-tier HetNet with macrocells, picocells, and femtocells, which have different backhaul capacities

## 2.3 Existing Intra-domain IP Traffic Engineering Schemes and Objectives

Selecting the right choice of TE features for emerging IP-access network follows the logic of the convergence of the cellular and Internet networks. In a similar manner, the convergence applies to aligning of the protocols, namely, network layer solutions for packet routing. While it can be argued that MPLS does offer convergence features, it is an add-on top of TCP/IP protocol suite with, as previously explained, significant protocol overhead and scalability issues. Thus, in this section we observe some proposals for IP-based TE for intra-domain networks,

while not disregarding the huge benefit of MPLS which are in controlling paths and multipath routing for redundancy and link utilisation maximisation purposes, to list a few.

Several Intra-domain IP-based TE methods have been proposed most of which build upon major common routing protocols OSPF and IS-IS. The two protocols are commonly applied intra-domain IGP hop-by-hop based protocols, that is, they are a standard part of the TCP/IP protocol suite deployed in the Internet inter-domain networks. It is notable that these, also termed as link-state hop-by-hop, routing mechanisms usually enforce Dijkstra-based algorithms for the link weight based discovery of a set of shortest paths [52–54]. Evidently, shortest paths are extremely helpful for best effort traffic and essential responsiveness to link conditions in networks marked by link weights, but as confirmed in [55] link-state hop-by-hop oriented OSPF and IS-IS ease of management and implementation does not suffice in improving the traffic engineering performance. Consequently, some non-link state approaches and source routing have been adapted. Hence, the drive is on overcoming these shortcomings of OSPF by seeking extensions, modification and development of efficient OSPF-based IP networking.

OSPF can be defined as an IP-based dynamic link-state protocol based on which a complete view of the network state and topology is rendered. OSPF is dynamic, scalable, reliable and robust against link/node failures. Nonetheless, OSPF's adaptation could cause network congestion which underscores the importance of traffic engineering application. Moreover, the arbitrary traffic splitting as enabled by MPLS is not supported by OSPF. Fortz and Thorup [27, 29] proved in pioneering foundational research that by optimal tuning of OSPF/IS-IS link weights aimed at load balancing by lowering the objective functions of maximum link utilization (MLU) and minimizing the delay approximated by a piecewise-linear function of M/M/1 queue, the networks performance could be significantly enhanced in comparison with the conventional link weight tuning configurations that apply inverse proportional bandwidth capacity [56]. In fact, it can rival MPLS performances in some scenarios although not have the same flexibility in switching between paths. To facilitate optimal configuration of paths based on link weights tuning, the most immediate improvement to OSPF can be via efficient

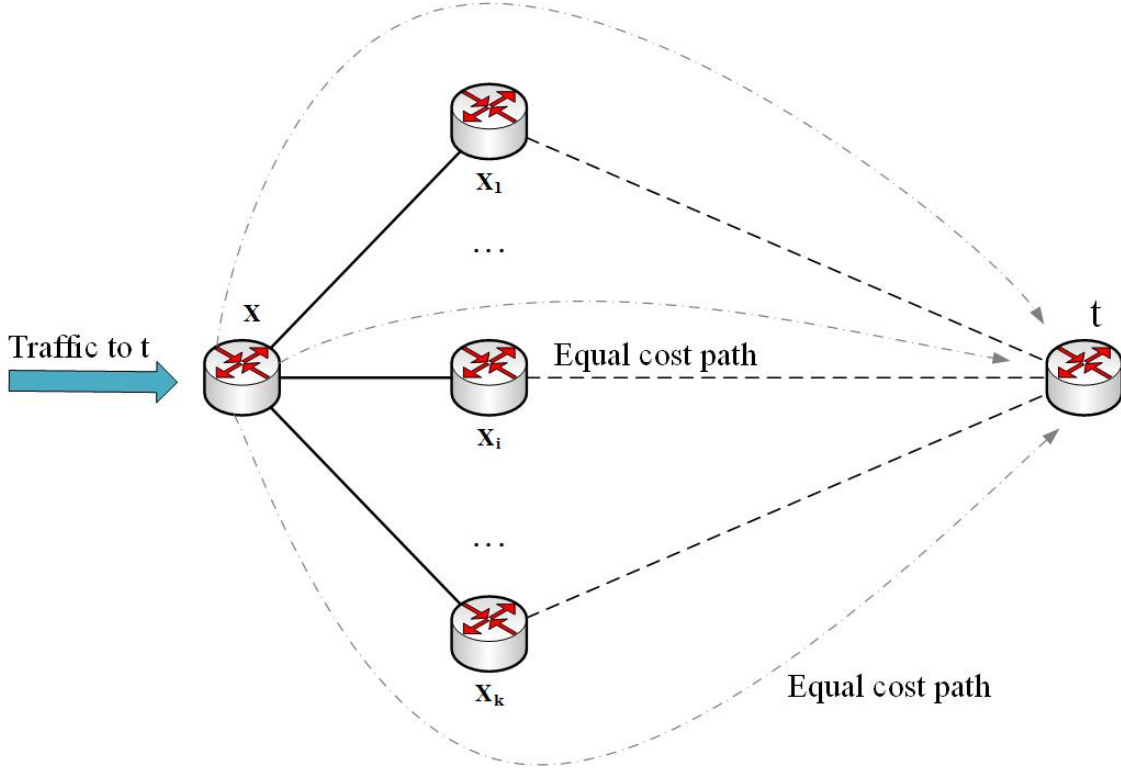
distribution of link weights information throughout the network via Link State Advertisements (LSA). A decentralized OSPF-based hop-by-hop solution is proposed in [23] aiming to accomplish optimality in a straightforward manner through the frequent distribution of Link state Advertisements (LSAs). The hop-by-hop mechanism adapted in this solution is expectedly shown to burden the routers in link weight computations and it is slow to converge, meaning that there is a significant time delay in triggering the need to recompute the paths based on new weight assignments and actual rendering of the paths in routers. In fact, there are quite a significant number of schemes that confirm this inflexibility as the major shortcoming of the default mechanisms of OSPF (further escalating in case of link failures [57]). In addition, real time - online changing of link weights in close relations to real time traffic dynamics is proven to introduce the risk of traffic looping in response to non-stable rendering of routing paths [58] (i.e. ping-pong effect).

Equal-Cost Multi-Path (ECMP) represents an add-on option of OSPF that was initially adopted and evaluated in [31, 33]. ECMP aims to tune the link weights so as to facilitate equal multipath traffic splitting through hop-by-hop forwarding in order to achieve load balancing that would rival MPLS-based approaches. Hence, there would be two or more (equal cost) paths between ingress-egress pairs in networks, provided that the summations of weights in the whole network when rendering these shortest paths between each ingress/egress pair, produces equal costs over different paths/routes. This weight tuning can be controlled and enforced but even from an intuitive perspective it depends on quite a few factors, topological configurations and link weights tuning. In fact, it makes ECMP highly intractable in case of diverse, large and random topologies especially for numerous numbers of sources and destinations as proven in [13]<sup>‡</sup>. Fortz and Thorup [31, 33] further showed that the traffic originally passing through one single path could be evenly distributed into multiple paths with equal OSPF/IS-IS weights based on ECMP. The study also showed that the optimal configuration of such link weights is NP-hard. Their proposed algorithm is illustrated in Figure 2.4. As it can be observed, the

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<sup>‡</sup>This is because the quality of OSPF TE can become arbitrarily poor compared to optimal TE due to the computational intractability to derive optimal link weights for large-scale networks

traffic flow originating from  $X$  to  $t$  is distributed evenly between the available paths. In this scenario, pre-emptive local adjustments must be made since shifting the traffic might cause extra congestion to other links.



**Figure 2.4:** Fortz and Thorups link weight optimisation solution

Several studies have been conducted on enhancing the optimality of IP intra-domain TE approaches via ECMP-enabled path diversity and the flexible use of the network topology [37,59]. However, all these ECMP-based approaches resort to link weight tuning in order to achieve path diversity which renders slow convergence, and decline in performance diverging from optimal TE. In order to address the common issues in ECMP, authors in [60, 61] have proposed a Network Entropy Maximization (NEM) based protocol that enables arbitrary splitting of traffic in case of ECMP. Nonetheless, the proposed protocols have slow responsiveness, either demanding entire equal paths calculations by routers [60] or rendering lengthy path re-configurations [60]. While ECMP can be a good solution for specific scenarios, it is intractable and inefficient for large flows (sub-optimal) [24].

In general, as discussed above, the IP-based schemes that are based on online EMCP or link weight re-convergence, although based on less protocol mechanisms than MPLS offer only a certain degree of responsiveness and benefits in specific scenarios or scopes. To increase the throughput potential of IP-based schemes via more (single or equal-cost) multipath routing, while still keeping their essential features as defined in the protocol suite of the IP network layer, a concept of multi-topology OSPF was introduced in [62] where there are several independent OSPF implementations that would be based on different link weight configurations and offer (offline) multipath routing in some types of (small-scale) intra-domain Internet networks. To facilitate the traffic distribution over different virtual topologies (i.e. planes), extra bits in packet headers were used in each IP packet to allocate them to specific topologies. Conclusively, multi-topology routing was analysed both in its offline and online modes of operations and evaluated as an attractive potential solution for overcoming the re-convergence issues in IP-based schemes and offering flexible multipath route installations as in MPLS [63]. A standard has accordingly been defined for such implementation of Multi-Topology OSPF (MT-OSPF) for intra-domain IP networks [64]

### **2.3.1 Why Do Next Generation Networks Need Path Diversity?**

In this subsection we observe another dimension in considering TE schemes for future access networks by focusing on architectural requirements on path distributions in network, rather than pursuing the optimality of routing solutions subject to performance criteria. The evolution of network devices, services and applications has reached a phase which imposes to rethink network design, making the case for a clean-slate design of future network paradigms. Correspondingly, the fast pace transformation of network services and applications calls for consistent adaptations in TE mechanisms. The significant rise of P2P approaches for gaming, telephony and television in conjunction with the surfacing of new traffic applications namely IPTV and VoIP and the revolutionary traffic types in the post-IP age highlights the fast evolution in networks. Equivalently, the abrupt traffic surges and variations, the increasing



traffic dynamism in line with the new traffic application types and the broad deployments of application-layer overlays must be accounted for. Another important contributing factor is the rise of traffic dynamism, that flash-crowd effects and widespread usage of application-layer overlays would undoubtedly exacerbate <sup>§</sup>.

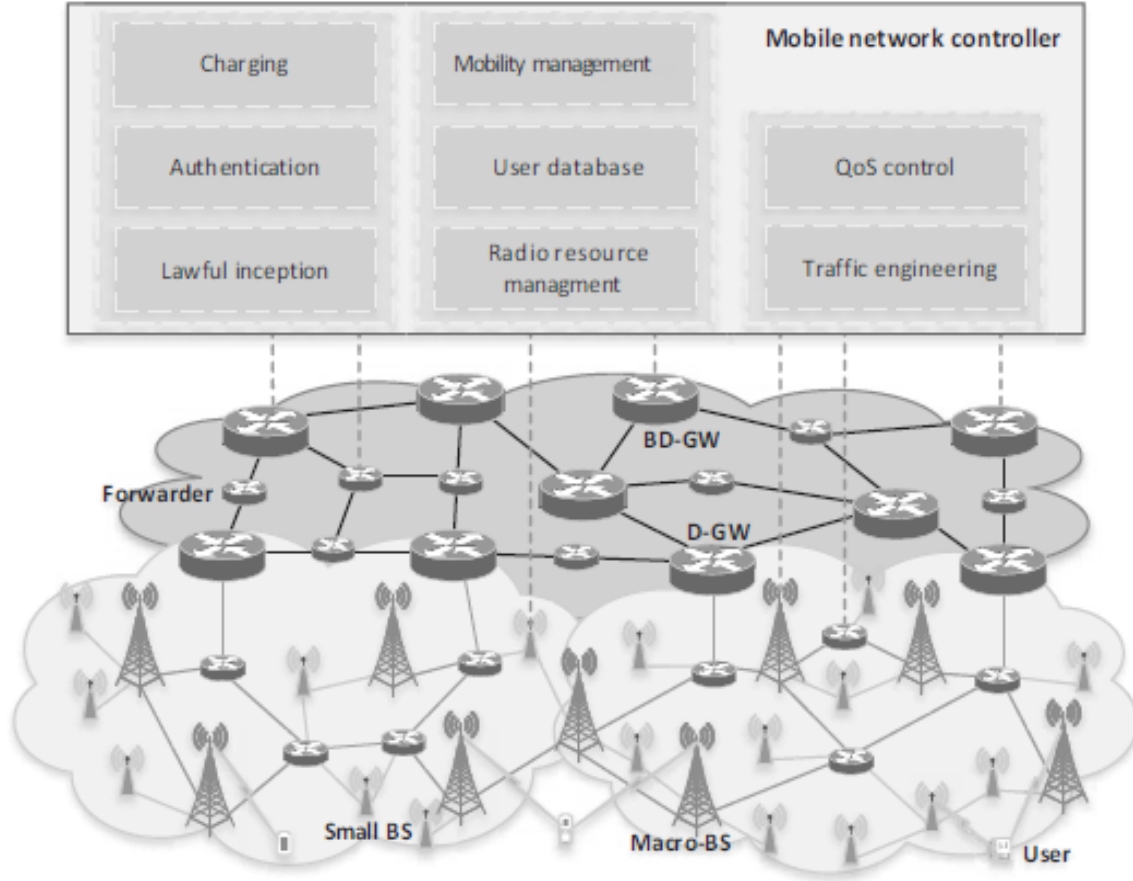
Correspondingly, the INPs have been increasingly considering multi-path routing which is aimed at minimizing the extent of over-provisioning (i.e. link capacity upgrade). The legacy dynamic routing could prove to be unstable and complicated while lacking the flexibility to adapt in face of congestion. Multi-path routing is generally more effective in taking advantage of the additional resources in a network to meet the incoming demands (avoiding link capacity upgrades). Therefore, Multi-path routing could represent a solid mechanism in present and future networks.

The mechanisms developed based on Multi-path routing must take into account different traffic applications characteristics and target enhanced performance based on diversity (facilitating the full utilization of network resources). Some traffic applications such as conversational calls and short Web transfers could still not be distributed into several paths. However, the majority of traffic types (e.g. file-sharing and live-streaming) are adaptive to dynamic environments which allows for a more straightforward exploitation of network resources.

Path diversity and its potential benefits in access networks was studied in [50]. The significance of future access networks' evolution with higher meshing in topologies aligned with the changes in heterogeneous access technologies was underscored by authors in [50]. It was suggested that path diversity enabled by multi-path routing needs to be exploited. The access networks must enforce native multi-path routing and flow control primitives to be beneficiaries of path diversity in the long run. Meanwhile, the wired backhaul links' overload [20] could be relaxed by the diversity offered by multi-path routing with the backdrop of the expected rise in the backhaul traffic [66].

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<sup>§</sup>In essence path diversity allows unrestricted or more flexible utilization of network routing resources, hence, contributing to the capacity of the network to be fully utilised. Such a practically founded principles has been confirmed in early investigations [65]



**Figure 2.5:** The illustration of SDN enabled 5G mobile networks

In this thesis, path diversity is considered as the underlying solution in case of all of our proposed strategies for enhanced network performance.

In addition, as also demonstrated in Figure 2.5, there is an emergence of new paradigms in routing that ought to be mentioned such SDN/NFV that are increasingly gaining popularity with the vision of next generation mobile networks (5G) being efficient and elastic to accommodate numerous and diverse services [25, 67]. SDN represents another approach that works by breaking down the abstractions that form the foundations of traditional networks, i.e. network layer into planes used for packet forwarding and control signalling. In doing so, path setup in networks is theoretically left completely open to situations and demands, hence allowing diversity and optimality to be superimposed in networks by relaxed creation of traffic

flow paths. In recent times, SDN solutions for routing are somewhat grounded from the initial conceptual vision due to extensive scalability and practical deployment viability concerns, but still valid in the forms of hybrid and dynamic solutions that can collaborate with conventional solutions used as foundations in this thesis. Such overlapping features include: lesser complexity in routers, router re-programmability and real-time monitoring of network traffic statuses, to name to most relevant. Similarly and founded on the same impetus of improving the hampering complexity of achieving relaxed and diversified routing in the conventional networks, is the new routing paradigm of segment routing [26, 68], that is proposed as a hybrid solution coupled with convention routing methods allowing freer and adaptable formations of routing paths in networks.

### **2.3.2 Multi-Plane Routing in IP Access Networks**

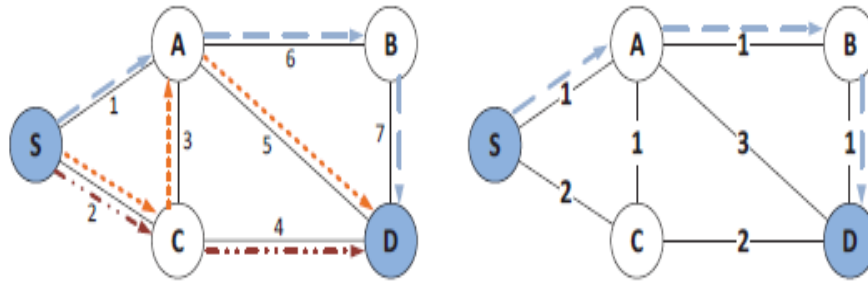
The continuous and extensive strive towards finding optimality in routing and suitability of TE models is indicative of the lack of general consensus and endorsement from the vast number of proposals proposed over a long span of time. Internet routing is still effectively at the same deployment and practical level of implementation where it was decades ago when it became widely used and available: MPLS or IP-based TE based on default IP routing protocols (e.g. OSPF for intra-domain routing etc.) families of solutions are still the divided choices for cellular and Internet based networks, respectively. As explained, convergence between the two types of networks is ongoing and imminent, as these emerging IP-based access networks (i.e. backhauls) will in future be the main access fabric towards the global Internet. Their characteristics are evident and break the rigid structures of the networks of the past: topologies are large, random, (wireless) access is heterogeneous, access distributions are dense, capacities of links are variable and opportunistic, shapes are practically adaptable, interconnections are often unplanned with relaxed structures of traffic flow arrangements etc. Hence a formulation of the approach that leads to the design of Multi-Plane Routing that is described in the following text consists of the several opportunities and gaps identified in the existing solutions and proposals:

- TE solutions for future IP-access networks need to be founded on practicality and ease of deployment with flexible and multiple path constructions as one of their most critical features. Due to the convergence of IP and cellular network layer(s), seeking an IP-based TE solution is a more viable option since the Internet transcends into one aligned functional space. Hence, protocol overhead can be seen from the point of view of adding more features to the default TCP/IP protocol suite, whereas MPLS adds the most overhead by including a sub-layer of extra protocol features.
- As advised in the literature, the solutions should combine both long-term and short-term planning and responsiveness attributed to offline and online segments of the TE solutions respectively.
- Solutions such as multi-topology routing for offline IP-based routing that add minimal protocol overhead or are already part of the TCP/IP protocol suite are a suitable candidate as they alleviate the routers from lengthy and complex path recalculations and very importantly offer path diversity.
- A suitable online mechanism should include both hop-metrics of multipath routing principles but also other QoS metrics when making packet delivery decisions. Hence, objective functions and QoS metrics should be practically focused into workable solutions with realistic computational complexities that offer the most efficient use of various underlying topologies.
- The solution should take into account many practicalities of the solution space: use of all links in the topologies, extensive range of performance criteria, localisation of processing in networks etc.

Multi-Plane Routing (MPR) which aims to address the deficiencies associated with MPLS and ECMP was initially proposed in [16] with further investigations in [17]. Analysis of practical aspects of MPR in extensive simulations for limited pre-defined tree-like topologies is

conducted in [17]. MPR is based on Multi-Topology OSPF (MT-OSPF) principle that was originally aimed for handling fast re-route in case of failures. MPR maximizes path diversity with minimal protocol overhead by employing MT-OSPF for comprehensive network-wide load balancing. Therefore, it increases networks' throughput capacity via the use of the entire topology [65] while utilizing multiple instances of OSPF for efficiency purposes [62]. MPR consists of an offline TE approach which constructs multiple path/RPs (i.e. instances of OSPF) and an online TE algorithm that governs the traffic flows over different RPs. The RPs are built so that an optimum full utilization of links based on Full Path Diversity Index (FPDI) is achieved as outlined in [16]. MPR's online TE approach was initially presented in [19] and [63] serving a practical purpose of an integrated solution of distributing IP sessions over RPs. MPLS TE approach's benefits namely explicit routing and arbitrary splitting of traffic are enabled through IP TE-based MPR. Therefore, the overhead and complexity of MPLS TE can be avoided through MPR with comparatively simple reuse of OSPF functions.

Three sets of shortest paths that are combined to form three routing planes in order to maximize path diversity (from ingress node S to egress node D) are demonstrated in Figure 2.6. These set of shortest paths should not be necessarily edge disjoint.



**Figure 2.6:** A simple example of 3 RPs. Numbers indicate link IDs (left) and link weights for one RP (right)

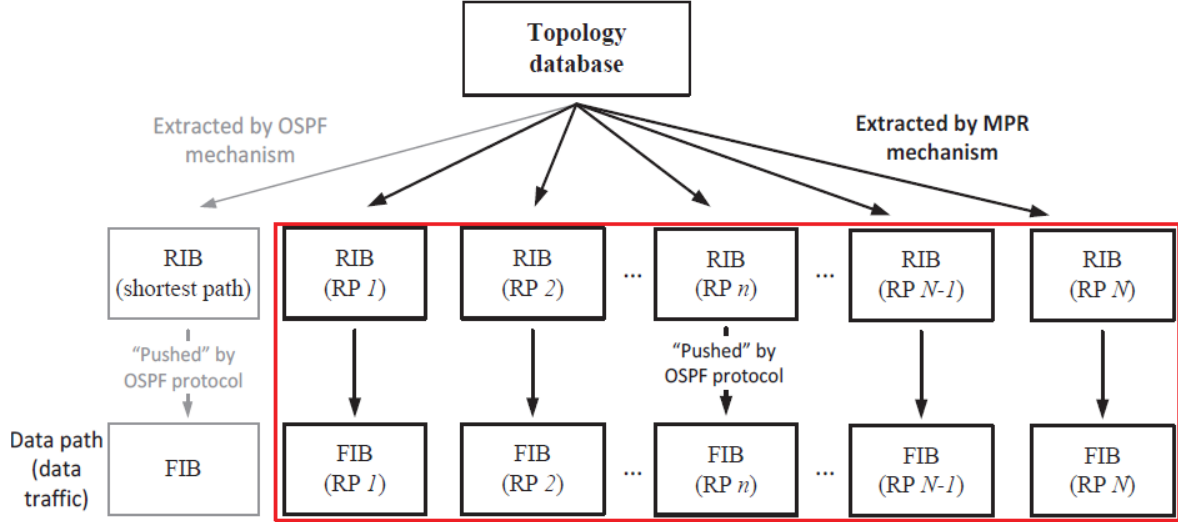
Figure 3.2 demonstrates the data flow in case of legacy OSPF and MPR. In case of the former, as also illustrated on the left side of Figure 3.2, one Routing Information Base (RIB, a routing table) corresponds to the topology database relating to the control plane followed by

one Forwarding Information Base (FIB, or a forwarding table) relating to the data plane being used. In case of MPR (i.e. bold lines in Figure 3.2), one RIB/FIB represents one routing plane. Therefore, flows are associated with specific planes as identified by routers and then routed based on the relating RIB. In terms of packet association with planes, there exist proposed solutions in literature for assigning traffic to RPs [69, 70]. Our proposed minimum set cover-based approach is also envisioned to exploit the same data flow structure as MPR.

MPLS TE approach's benefits namely explicit routing and arbitrary splitting of traffic are enabled through IP TE-based MPR. Consequently, the complexity and overhead of MPLS TE can be avoided through MPR. Some proposals have recently emerged [71] that adapt practicality in bridging the characteristics of IP-based/destination-based routing (e.g. OSPF IP-based routing) and explicit routing (e.g. MPLS). The underlying significance of path diversity in future access networks has motivated further studies on MPR in [72] and [18] which form the foundations for this thesis. Early results with the added internal traffic distributions for one topology are presented in [18] with the modified online TE approach in comparison with [19] and [63]. [72] proposes a novel comprehensive multi-topology routing optimization scheme for random access network structures with a fundamentally different offline TE methodology redesigned to suit random graphs where MPR's approach is deficient. Furthermore, the proposed mechanisms are compared with rival IP and MPLS based TE mechanism in terms of online network metrics.

### **2.3.3 Quality of Service**

Internet has been best effort for long treating all traffic packets (e.g., data, voice, video) the same without implementing QoS provisioning. This best effort treatment and capacity upgrades through the Internet are proving not to be viable solutions for much longer given the significant rise of traffic volume and the corresponding QoS sensitive traffic applications. Correspondingly, the adaptation of service differentiation oriented models is becoming increasingly vital. In the meantime, traffic applications throughout the Internet require stringent QoS



**Figure 2.7:** Data flow in case of legacy OSPF and MPR

enforcements associated with the corresponding Service Level Agreement (SLA). The evolutionary access networks (both Internet-based and cellular) must become more adaptive in terms of compatibility with service differentiation models in view of the increasing end-to-end QoS requirements [43]. In case of real-time services (e.g. video on demand, VoIP), SLAs guarantee QoS requirements such as low jitter, packet loss and end to end delay while ensuring a healthy throughput achievement. We should note that problems consisting of two or more additive QoS constraints have proven to be NP-hard [68]. However, QoS enforcement in packet switched access networks render multiple challenging issues since there are several aspects of QoS to be considered. The high throughput and hence the corresponding high bandwidth provisioning required to back up video communication exemplifies such challenges. Meanwhile, audio communication does not really demand high bandwidth. Jitter (i.e. delay variations) and latency (End-to-end delay) are significant factors to be considered in case of time-critical traffic types. Over the course of the last few years, an Internet generation (i.e. tactile internet) has been considered that supports Haptics communication in addition to voice and data communications. This new Internet dimension is associated with strict QoS criteria namely extremely high reliability which corresponds to very low packet loss along with low latency and jitter.

Moreover, the rising multi-gigabit backhaul traffic must be catered for in increasingly dense cellular networks while ensuring QoS requirements associated with the fast rising users' expectations [66]. [73] details the efficient usage of network resources in case of flow-based QoS routing while aiming to select optimum routes base on QoS constraints.

QoS architectures can be categorized into two fundamental elements: Differentiated Services (DiffServ) [74] and Integrated Services (IntServ) [75]. IntServ was originally put forward in order to handle the variable queueing delays and traffic overloading losses. This was specifically targeted at the rising real-time applications like remote video, multimedia conferencing, visualization, and augmented/virtual reality [76]. A packet's traffic class is determined based on a signaling protocol which guides the routers on how to treat the concerning packet. End-to-end QoS provisioning per flow state requirements (i.e. mapping QoS to specific flows) is facilitated through this architecture. IntServ enables QoS by applying reservation through Resource Reservation Protocol (RSVP) of end-to-end paths to broadcast the QoS metrics throughout the network. The transmission will start once the bandwidth criterion is met for a selected path. Two types of services namely controlled-load service and guaranteed service are supported by IntServ architecture. Guaranteed service imposes tough limitations on bandwidth and end-to-end delay for any traffic type with such reservation requirements [77]. Meanwhile, controlled-load service facilitates a low latency and better than best effort service under light to moderate network loads.

DiffServ model which represents another major QoS architecture model was introduced to enable service differentiation omitting the signalling based per-flow state treatment in every router. Under DiffServ, packet's class can be marked in the IP header (IPv4 ToS octet or the IPv6 traffic class octet) in order to enable the required forwarding treatment at each network's router. The DiffServ model benefits from better scalability and versatility and comprises two main elements: forwarding plane (data) and management (control) plane [78].

Finally, we should note that these two QoS architectures are not mutually exclusive and could be implemented in conjunction.



## 2.4 Summary

In this chapter, the literature review containing the fundamentals and related work was presented. The ubiquitous IP infrastructure and evolution of cellular network are presenting new opportunities for INPs. In the meantime, Internet has undergone significant transformations with the huge increase of traffic volume and the corresponding escalation of new traffic applications. The surfacing of Tactile Internet is a reflection of the rising new traffic applications that are traversing the Internet imposing new stricter traffic flow requirements. In consideration of these transformations, it is becoming increasingly essential for INPs to apply routing optimization. In addition, the architectural transformation of all-IP access networks is consistent with the evolutionary 5G and networking concepts also require coordinated adjustments in TE mechanisms. Moreover, the expected increase in access density, heterogeneity and complex random structures need to be taken into consideration. Path diversity was presented as a significant underlying integrated routing optimization factor in access networks. MPRs TE mechanism which incorporates path diversity in its approach, aims to facilitate a comprehensive IP-based intra-domain TE solution for the evolutionary all-IP access networks. Correspondingly, Minimum Set Cover (MSC) which also adapts path diversity in its approach will be proposed as an intra-domain routing optimization methodology for future randomly shaped heterogeneous access network structures.

In the upcoming chapters (chapters 3-6), MPR will be adjusted in order to mirror some practical aspects namely the architectural evolution of IP access networks with the backdrop of a comprehensive traffic distribution model followed by considerations for the surfacing of Tactile Internet applications. In addition, MSC will be proposed in consideration of the unpredictable and expected heterogeneous substructure of future all-IP access networks. To this end, extensive offline and online performance analysis testing the suitability of our approach for complex random network structures (where MPR is deficient) will be presented coupled with comparisons against rival strategies.

# 3

## **Multi-Plane Routing-based Load Balancing Strategy for Future Link-State Convergent All-IP Access Networks**

### **3.1 Introduction**

In consideration of the significant surge in the global IP traffic, service providers must adapt to facilitate disruption and loss free networks supported with the ubiquitous IP infrastructure. Meanwhile, radio access networks are moving towards a flat-IP architecture in the backhaul with the disposal of the hierarchical network structure. To this end, a routing optimization mechanism must be developed which applies suitable Traffic Engineering (TE) techniques in consistent with the evolutionary nature of future access networks. In this chapter, MPR that integrates various aspects of an all-IP infrastructure is extensively modified and analyzed in evolutionary access network structures. It is envisioned for MPR to be configured using the IP-header integrated ToS/DiffServ's unused bits (i.e. 3 precedences) in view of reduced overhead. MPR-based TE strategy is adjusted to incorporate two different scenarios in order to reflect the evolution in the architectural design of access network structures. The study considers a

realistic traffic scenario with a varying range of internal/external traffic to provide practicality and comprehensiveness. Accordingly, a practical performance evaluation testing the validity of the aforementioned scenarios is presented. It is convincingly shown that for ranges of topologies, MPR's utilization of the whole topology in building path diversity in networks allows for significant improvement of networks capacity, performance and support for meshing.

Furthermore, the Tactile Internet which represents another practical application of MPR, is accommodated in this chapter. To this end, a novel reliable MPR-based routing scheme is laid out in consideration of the strict Tactile Internet's characteristics and requirements. This proposed policy is based on MPR that consolidates various aspects of an all-IP access infrastructures and enables network-wide path diversity as discussed. It will be discussed based on simulations that the proposed policy outperforms intra-domain routing protocols namely OSPF and performs near-optimally. Consequently, it will be argued that shortest-path solutions such as OSPF cannot be applied in order to handle haptics communication in typical Internet network topologies.

## **3.2 Analysis of Practical Architectural and Traffic Flow Aspects**

### **3.2.1 Background Discussion on the Practicality**

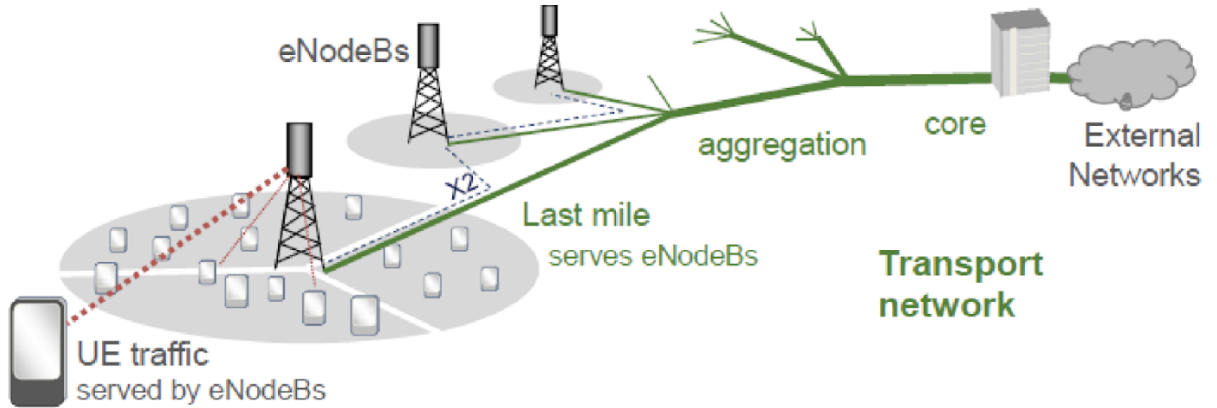
Further to the general background and aspects of evolutions of IP access network associated with advances in routing protocols and TE schemes as discussed in Chapter 2, some dedicated explanations are contained in the following text from a perspective of analysing the network structures, topologies and practicalities of deployment. Intention is to elucidate on the background to network developments and its relevance to the design of multi-plane routing. This means fitting of the TE solutions with deployment considerations and instantiated degrees of convergence of the Internet and cellular networks, the very convergence being of the primary

design target space for the multi-plane routing.

Synergies of native IP (access) networks with cellular networks deal with ubiquitous spreading of native TCP/IP protocol suite and its constant advances as the sole network and transport layer glue. Such a possibility was pinpointed a while ago in many visionary works during the initial deployments of generations of digital, packet-based cellular networks (2G, then visions for 3G and so on [4, 5]). An underlining assumption of this process of convergence is that the cellular networks (often termed as mobile networks) are to operationally merge the protocol tools and architectural layouts with Internet networks. In the design of Internet networks these are the dedicated domains of intra Autonomous Systems (AS) networks that deploy intra-domain routing protocols, while in the design of cellular networks, these are the (core/access) network architectures and topologies that have been changing with each new generation. On the side of Internet networks, the protocols of the suite are subject to constant advancements, being the objective of this work as well, and happen under the standard process of TCP/IP protocol suite designs of the segments of the Internet protocols (e.g. via research or the works of standards body such as Internet Engineering Task Force IETF). Typical Internet IP access networks [79–81] are still referring to campus or metropolitan areas network encountered in universities, companies, then, INPs metropolitan areas IP networks etc; all of these have been subject to a long line of research for suitable IP mechanisms that guarantee more than just best-effort deliveries. Regarding the cellular networks, more explanations on the related evolutionary aspects of the generations of cellular networks is given in the following.

Simplistically, the convergence refers to how much do the features of the cellular networks come close to having the same protocols deployed as in the native Internet networks. As discussed in the previous chapter, the choice made is to focus on IP-based routing solutions and TE, eliminating the extra features needed to run MPLS. In the evolutions of cellular networks, after the introduction of packet-based transport in 2G (via specific network layer tunnelling protocol General Packet Radio Services - GPRS), a major stepping stone towards the ultimate convergence occurred in 2000s with the rollout of 3G when users were provided with constant

access to the Internet [82–84] over the specific cellular networks protocols. While this ubiquitous access to the Internet has remained, the underlying structures of the cellular networks and the qualities of packet deliveries have continued to augment. A significant change in the structural compositions of the network architecture occurred in 2010s with the introduction of IP core transport in 4G (i.e. Evolved Packet Core EPC), where all circuit-switched telephony was abolished and IP-based communication was established in the core part of the cellular networks for IP telephony [85, 86]. The specific access networks (i.e. RANs) still remained with dedicated packet delivery, but the layout provided a constrictive scenario for the transition to IP-access networks that is still ongoing with recent 5G developments. This is currently marked by two design features of cellular network that define the convergence momentum: flat IP end expansion of backhaul.



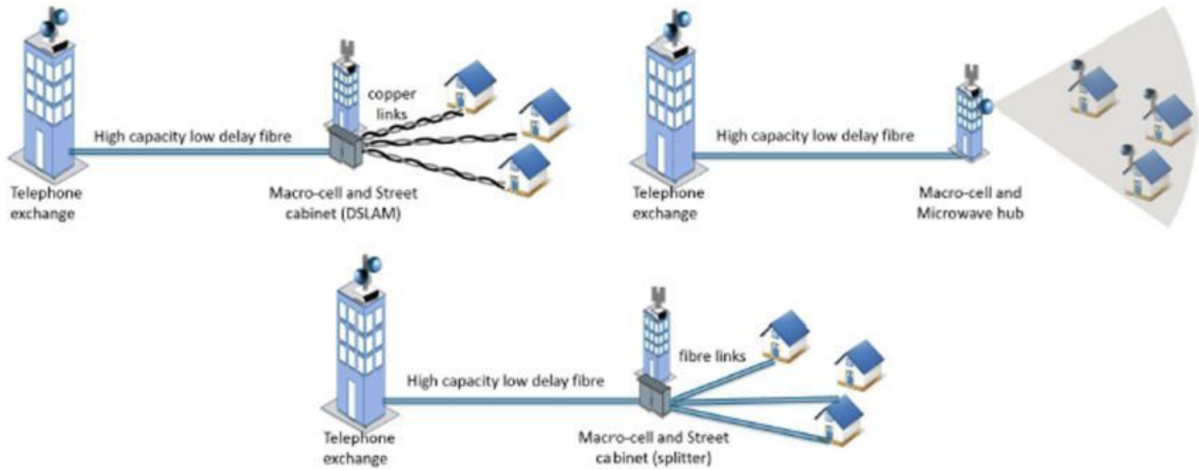
**Figure 3.1:** Structure of 4G network (LTE/EPC) in terms of traffic flow distribution points and interfaces

Flat IP concept marks the transition to 4G cellular networks and beyond, being a constituent operational feature for further facilitation of IP proliferations inside the structures of cellular network architectures in 5G [87]. Effectively, flat IP means that the IP access is achieved directly, that is, at link layer level of a BS/Access Router/eNodeB rather than at the interfacing point of the (radio) access network and IP core (e.g. Radio Network Controller entity in the network). This change was greatly facilitated by the adoption of X2 interface in cellular network standards that provided for a direct, horizontal, communication between BSs/eNodeBs [88], also shown in Figure 3.1 (also represented in the experimentation Case II explained at the end

of this subsection). Consequently, IP addressing and transport moved down to the very radio access level. However, as the network layer for carrying IP traffic is has remained cellular-standards-based rather than native TCP/IP, the IP addressing is symbolic rather than following a hierarchical structure of routing and addressing as in the native IP networks. The IP flattening marked another important architectural transition: abolition of the separation between the core and access effectively making the entire cellular network constituting one or more IP access networks with near default IP structure and having dedicated gateway functionality towards the rest of the Internet. It also forms the hypothesis and vision for this work that convergence of IP networks and cellular networks will be entirely operational with adequate TE schemes such as multi-plane routing.

Backhaul networking has received great attention in parallel to the evolution towards 5G networks, initially being focused on the radio access technologies and advancement in the features of Radio Access Networks (RAN) [6-8, 20, 40]: from wireless technologies, QoS considerations, security features, user mobility and so on. While topological issues were marked as challenging in the backhaul networking due to potential shortages of link capacities [20], dedicated TE for access networks and backhaul structures often received considerations in terms of research directions for the new technological options such as SDN [56]. Only very recently, and somewhat finally confirming the vision that founded the works on multi-plane routing in this thesis, backhaul networking and associated topologies are becoming highlighted as the next stepping stone in development of cellular networks [82]: In addition, a new network bottleneck has emerged: the backhaul network which will allow to interconnect and support billions of devices from the core network. Similarly, the survey also confirms the initial projections in the design of MPR and outside conclusions at the capacity problems [20] in the backhaul network topologies that interconnect heterogeneous dense cell deployments[113]: Due to the dense small cell deployment and heavy traffic cells in 5G, 5G backhaul network will need to support hundreds of gigabits of traffic from the core network and today's cellular backhaul networks are infeasible to meet these requirements in terms of capacity, availability, latency,

energy, and cost efficiency . Going back to the discussion from Section 2.3.1, the emerging IP access networks need path diversity in their topological structure to compensate for the great demand in capacity and traffic requirements. The randomness of topologies becomes greatly influenced by the dense and heterogeneous cell layouts from macro, micro to femto cell levels. Topological randomness and meshed interconnection become dictated by the practicalities of engineering the connections and laying out the access points in real life environments (e.g. urban environments such as floors, buildings, campuses, cities etc). Finally, the physical interconnections vary and are dictated by the business cost models and physical configurations of terrains and can range from optical fibres to copper wires to recent new technologies for point-to-point and point-to-multipoint wireless links. Some elemental layouts of topological stem constructions are given in Figure 3.2.



**Figure 3.2:** Example stems of practical deployment cases of topological layouts, clockwise: copper links, point-to-multipoint wireless links and optical fibre links [112]

The structure of IP access networks calls for new considerations in IP-routing mainly due to envisioned tree-like topologies. Access networks are generally comprised of a transit routing space that connects the access nodes to the core network through gateway. Traffic flows between gateway and access nodes in both directions, and between access nodes. Such access network structures are necessitated by the practical requirements of deployments. These requirements dictate network planning to conform with diverse topological layouts of hetero-

geneous access points and deployed infrastructures. In the recent evolution of networks [20], randomness of topological layouts imposes novel challenges for TE due to expected capacity constraints in backhaul links of interconnected femto, pico, micro and macro accesses. Furthermore, novel user mobility models have emerged for these network access structures aligned with the 5G development [89].

A reference scenario was studied for MPR in [63] and [19] where the RP structure's construct was such that only dedicated RPs (i.e. paths) for every *Gateway (GW)-Aggregation Router/Access Router (AR)* pair were considered. Under this scenario, GW was considered to be the only possible anchoring point of traffic in the network, hence, bulk of traffic in the network would have been of downlink nature (Aggregation Router assumes a case of topological stems as depicted in Figure 3.2 such as aggregation of wireless point-to-multipoint multipoint links). Moreover, all the traffic was assumed to be external (i.e. have emanated externally) with the possible existence of internal traffic between the ARs being neglected.

We extend and complete the analysis of MPR in access network structures by studying and comparing two cases considering the existence of both internal and external traffic (with both uplink and downlink nature) with the possibility of all the ARs and the GW being sources and destinations of traffic:

- Case I: The RP structure is comprised of multiple *GW-AR* pairs. This design concept is restricted to 3G environment's architectural functionality where the entire traffic destined for outside of the network towards the big Internet and the internal traffic between the ARs would pass through the GW. We are targeting to expand this model to converge the Internet routing and future cellular systems' requirements by modifying the RP structure, allowing for direct communication between the ARs as reflected in the design concept for case II.
- Case II: In this case, the RP structure is modified by including direct communication paths between ARs in addition to the duplex *GW-AR* pair, hence deploying the IGP's operation in full (i.e. OSPF). Our design concept is equally reflected in the trends towards



a flat-IP structure in cellular networks, as explained previously, where the increasing need for such structure has been emphasized [8, 90]. Accordingly, base stations are directly interconnected by IP and the forwarding domain barriers in these networks (i.e. radio access and core networks) are being abolished making the new backhaul connection space open to diversification of paths via meshed hierarchical topological set-ups (i.e. from 4G onwards). In fact, with the expected increase in the backhaul traffic [66], wired backhaul links' overload could be alleviated by the diversity offered by MPR [20].

### 3.2.2 Concept

MPR divides the physical topology into multiple logical planes called RPs. Each RP is an instance of OSPF associated with a dedicated link weight configuration and it can overlap with another or share any subset of the underlying network \*. MPR applies path diversity in building RPs using an offline algorithm that leads to the full utilization of resources (i.e. links) in the network. All the routers will have different Routing Information Bases (RIBs) (i.e. control plane) and Forwarding Information Bases (FIBs) (i.e. data plane) through which routes are defined in every RP. Each RIB/FIB represents one RP. MPR is originally envisioned to exploit the bits available in the Type of Service (ToS) field of IP packets, specifically, DiffServ integrated bits. DiffServ that was put forward by IETF in [91] is designed to facilitate multiple requisite QoS in the network and it supersedes the obsolete Type of Service (ToS) field whose bits are re-branded in DiffServ. Hence, in case DiffServ is used, there would be three unused bits (the fifth, sixth and seventh precedences) that can be used by MPR to mark each plane allowing up to 8 RPs to be supported. In case DiffServ is not used, MPR would have access to more bits, hence, more planes could be supported by ToS field (same or extended availability applies for IPv6 headers). Routers are configured to recognize the RPs through the unused bits. It was shown in [16] that up to 5 RPs are sufficient in case of MPR for similar network topologies as also substantiated in [69] for MT-OSPF. Consequently, MPR can exploit the

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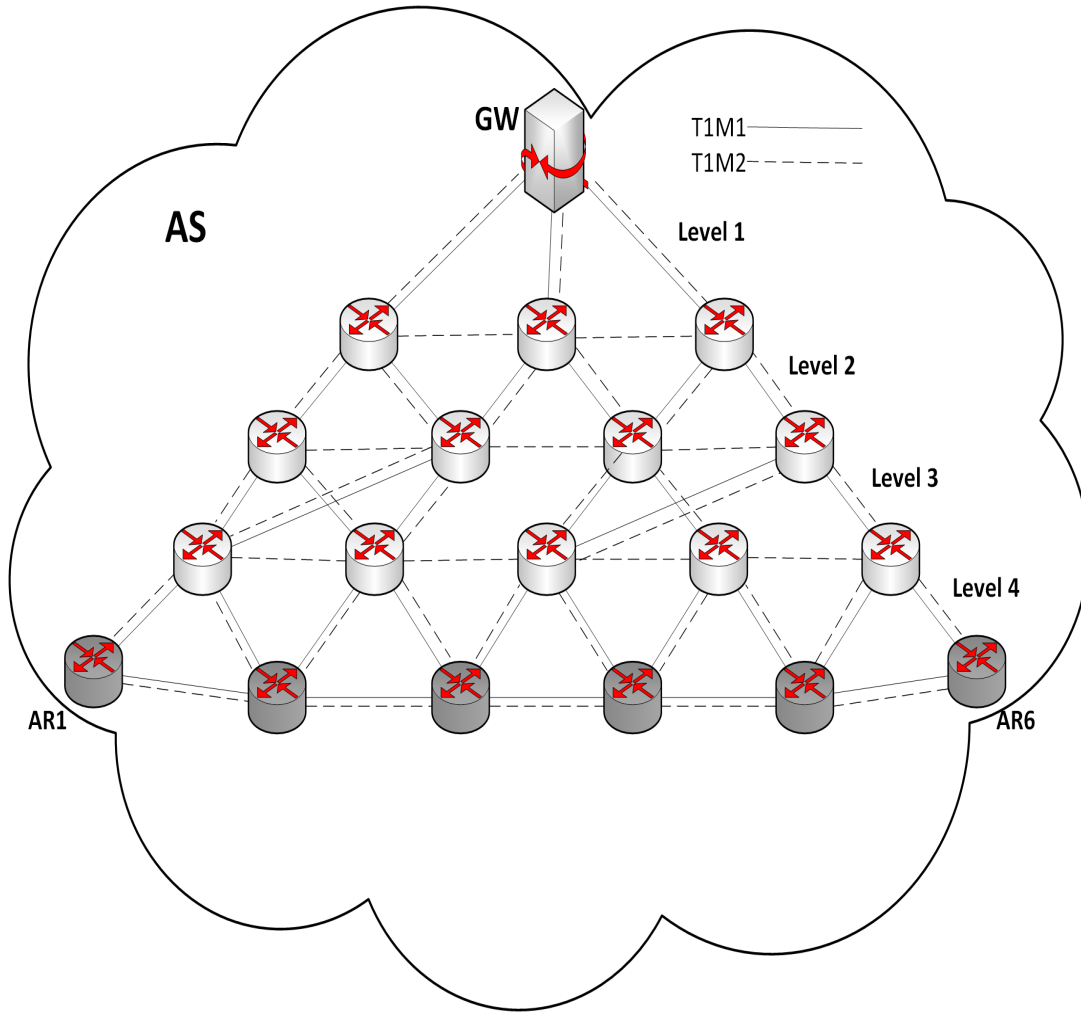
\*We do not exclude the possibility of equal-cost multi-paths (ECMPs) occurring in the OSPF configuration of a RP. Regardless, each RP is used as one independent path diversity option from the *Ingress* to the *Egress*

structure in the IP header without imposing extra overhead onto each packet. This is opposed to MPLS where a 32-bit MPLS label stack is imposed on the IP packet by encapsulation causing overhead and router's configuration complexity.

MPR does not impede IP host mobility management solutions in IP access networks, neither end-to-end mobility (i.e. mobile IP) nor uses of mobility agents in access networks. MPR's routing solution runs separately from the mobility management functions such as tunnelling and IP address allocations. Since MPR also supports internal traffic as proposed in this paper, when mobility agents are used, traffic to and from them is subject to regular decisions of the MPR's online algorithm at the *Ingress* points. Hence, MPR supports any location of mobility agents in access networks. Traffic load balancing with MPR's online algorithm can coexist with load balancing solutions via mobility agents in similar access network topologies [92]. In case of the projected user mobility model for future 5G networks [89] that include coverage of heterogeneous cells, MPR would treat the occurrences of varying traffic from mobile users as a uniform scenario at the network layer. To this end, MPR's online TE model is expected to adapt accordingly as to cease up the routing resources/paths in the whole topology caused by the unbalanced traffic injection to and from the *Ingress* aggregation router(s) (i.e. serving cell(s)).

### 3.2.3 Simulation Setup

Before formulating the simulation scenarios and network and traffic performance parameters, some further explanation is dedicated to the applied practicalities of IP access networks used in the study. The convergence of Internet and cellular edge networking into the IP access networks does not straightforwardly assume a topological structure that is overabundant in capacity and ideally composed and interconnected via the most suitable topological configurations. Internet and cellular networking links have typically grown in capacities, e.g. following the Ethernet upgrades, in the order of tens to hundreds of Mb/s and more, whilst likewise, fibre links conveniently provide more than 10 Gb/s link capacities. As noted in the previous parts of



**Figure 3.3:** Autonomous system comprised of 19 nodes and 32/41 links. Average node degree: 3.36/4.32. Total capacity (Gb): 11.94/15.34 ( $T_1$  topologies are illustrated, Table 4.2)

the thesis, several major issues still define the capacity as a scarce resource in future IP access networks due to: a) engineering and deployment cost requirements; b) densification of cells access and the resulting topological layouts; and, c) significant increase in traffic demands and introduction of new traffic types with extremely stringent traffic requirements on packet loss, delay and jitter as studied in latter parts of the thesis for the case of tactile traffic. Hence, the topological layouts and available links capacities for IP access networks are becoming much more random and sparse, especially when compared to layouts and parameters in conventional Internet data-centres or inter-domain routing networks.

Complete coverage of fibre optics right to the edges of the network is not commercially

viable and often too slow and bulky to engineer, in fact, some figures from recent years show a very small (less than 14% in 2014) penetration of fibre links in most of the European countries and an unsustainable growth of traffic demands compared to backhaul capacities [88, 93]. In cases of dense cell deployments these inhibitions are more emphasised. Hence, combinations of fibre, copper wires and wireless point-to-point and point-to-multipoint technologies are expected to be used as practical necessities [82, 94] and they can range from 10Mb/s or less (e.g. copper and wireless mediums prone to degradation due to weather and line of sight scenarios) to several hundreds of Gb/s link capacities in case of optical fibre [82, 88]. As elaborated below, topologies and configurations used in this thesis reflect these practical observations: this Chapter providing a study based on facilitation of IP access network routing in topologies that can be considered a converged networks tangible in today's terms in typical urban environments and scope, while the next Chapter foresees more random dense cell deployments and larger topologies that are to be expected in future proliferations of IP access networks.

Finally, as discussed in Chapter 2, the traffic conditions in access network are to be handled by combinations of offline and online mode responsiveness with no predictable input of Traffic Matrix (TM). Consequently, scenarios of traffic types and distributions of loads on links and in the overall network are most appropriately emulated via a standard approach of link capacities normalisation and variable traffic demands experiment that enable insights into light and heavy loading conditions in the network.

The network in Figure 3.3 represents an Autonomous System (AS) which constitutes a metropolitan or campus access network with a single gateway towards the big Internet. This reference fat-tree model is based on [42] where a meshed tree-based structure design has been suggested over other architectural designs as networks will have a significantly larger number of base stations and a much higher bandwidth demand at their edges (i.e. access points). TABLE 4.2 presents the specifications of the set of topologies of different meshings. Nodes are considered to be interconnected by wired Ethernet links. A  $M/M/1$  queuing model is considered for every node. Topology 1 consists of 6 base stations acting as Aggregation Routers

**Table 3.1:** Setup of the topologies

Topo	Nodes	ARs	Links	Avg. Node degree	Total capacity (Gb)	No. of RPs
$T_1M_1$	19	6	32	3.36	11.94	4
$T_1M_2$	19	6	41	4.32	15.34	5
$T_2M_1$	32	14	53	3.31	15.28	3
$T_2M_2$	32	14	67	4.19	18.40	5

(ARs). Link capacities are randomly set up following a uniform distribution in [360, 400] for Level 1, [200, 240] for Level 2, [140, 180] for Level 3 and [60, 100] for Level 4 in the first topology studied (19 nodes). The second network studied (32 nodes) contains 14 ARs that are randomly distributed in the network as opposed to being strictly placed at the edge to provide more random configurations of networks. This topology is comprised of five levels where link capacities are generated in the following intervals: [360, 400] for Level 1, [160, 200] for Level 2, [110, 150] for Level 3 and 4, and finally [50, 90] for Level 5.

### 3.2.4 Graph Theoretical Representation

Let the topology of a given communication access network be represented by a connected directed graph  $G = (\mathcal{V}, \mathcal{E})$ , with a set  $\mathcal{E} = \{e : e = 1, \dots, E\}$  of edges with finite capacities  $C_e$ , and a set  $\mathcal{V} = \{v : v = 1, \dots, V\}$  of vertices. Let  $\mathcal{K} = \{k : k = 1, \dots, K\}$  symbolize the number of ARs in the network whereas the GW is symbolized as  $K + 1$ . Let the set of Routing Planes (RPs) be represented as  $\mathcal{N} = \{n : n = 1, \dots, N\}$ . Every  $e \in \mathcal{E}$  is assigned with  $N$  distinct link weights denoted by  $w(n, e); \forall n \in \mathcal{N}$ . The network supports a set of overall traffic flows for every *Ingress* - *Egress* pair that are referred to as demands and is denoted by  $\mathcal{D} = \{d : d = 1, \dots, D\}$ . In addition to the GW as a possible source of traffic, let  $AR_{\mathcal{A}} (\subseteq AR_k)$  be the source AR ( $\mathcal{A} = \{a : a = 1, \dots, A\}$ ). The *Egress* nodes are:

$$Egress : \begin{cases} \{AR_k\}_{k=1}^K, \text{ when } GW \text{ is } Ingress \\ \{AR_k\}_{k=1, k \neq a}^K \cup GW, \text{ when } AR_a \text{ is } Ingress \end{cases} \quad (3.1)$$

$AR_{fi}$  represents the first destination AR while  $AR_{la}$  represents the last destination AR in the network in one path set ( $\rho_n^k$ ) pertaining to a particular source in the iteration. Subsequently, the source AR ( $AR_a$ ) changes for the next iteration until all the ARs and the GW are covered (i.e. an instance of OSPF, one RP). The connections are duplex therefore, all the destinations can be sources as reflected in the overlapping RPs built for all the ARs and GW. Every RP is comprised of  $\rho_n^K = \{\rho_n^k : k = 1, \dots, K+1\}$  set of shortest paths.  $\rho_n^K$  incorporates the demand-set  $\mathcal{D}$  for  $\{P_n^d\}_{d=1}^D$  in RP  $n$  for all the ARs and GW. Therefore, there are  $\{P_n^d\}_{d=1}^D \subset \rho_n^K$  acyclic shortest paths for RP  $n$  according to the link weight configuration  $W_n$  for that RP. The position of every link in path  $P_n^d$  is represented by a set of  $\mathcal{H}_n^d = \{h : h = 1, \dots, H_n^d\}$  hops from the *Ingress*. An  $N \times E$  matrix  $R^d$  represents the link usage.  $R_{eP_n^d}^d = 1$  if path  $P_n$  of pair  $d$  uses link  $e$  and  $R_{eP_n^d}^d = 0$  otherwise. Matrix  $R^d$  for demand  $d$  is:

$$R^d = \begin{bmatrix} R_{1P_1^d}^d & R_{2P_1^d}^d & \cdots & R_{EP_1^d}^d \\ R_{1P_2^d}^d & R_{2P_2^d}^d & \cdots & R_{EP_2^d}^d \\ \vdots & & & \\ R_{1P_N^d}^d & R_{2P_N^d}^d & \cdots & R_{EP_N^d}^d \end{bmatrix} \quad (3.2)$$

Path Diversity Index (PDI) as originally presented in [16] represents the number of RPs that include  $e$  in their shortest path for demand  $d$ :

$$PDI_e^d = \sum_{n \in \mathcal{N}} R_{eP_n^d}^d \quad \forall e \in \mathcal{E} \text{ and } \forall d \in \mathcal{D} \quad (3.3)$$

The ultimate objective is to minimize the chance that for a given demand all RPs share a single link; secondly to maximize the chance that any link is used in at least one RP. Full Path Diversity Index (FPDI) is introduced in [16] which designates whether a critical link  $e$  is included in shortest path for pair  $d$  in all RPs. FPDI is equal to 1 if  $PDI_e^d = |N - 1|$  and 0 otherwise. The link weight assignment is described as follows: to calculate  $|N|$  set of positive link weights  $W_n = w(n, e) : 1 \preceq w(n, e) \preceq L$ , with  $\forall n \in \mathcal{N}, \forall e \in \mathcal{E}$  and  $L (= 2^{16} - 1)$  as the

highest value that OSPF can handle in order to maximize:

$$\sum_{d \in \mathcal{D}} \sum_{e \in \mathcal{E}} FPD I_e^d \quad (3.4)$$

The set of path matrices  $(\rho_n^1, \rho_n^2, \dots, \rho_n^K, \rho_n^{K+1})$  for all the ARs and GW represent one RP.

$$\rho_n^k = \left\{ \begin{array}{ll} AR_S & . \quad . \quad . \quad GW & : P_n^{d_k=1} \\ AR_S & . \quad . \quad . \quad AR_{fi} \neq AR_S & : P_n^{d_k=2} \\ \vdots & \\ AR_S & . \quad . \quad . \quad AR_{la} \neq AR_S & : P_n^{d_k=K} \end{array} \right\} \quad (3.5)$$

The AR-GW pair is reserved in every RP for the case that the network ID of the desired address is located outside of the network and vice versa.  $d = 1$  represents the AR1-GW pair in path-set  $\rho_n^1$  and the demand increments up to  $D$  corresponding to the final pair in path-set  $\rho_n^{K+1}$ .  $\bar{\phi}_s$  is represented as the average length of the shortest path in terms of hop-count from any source  $u$  to all the destinations  $v$  across the available planes under a given topology.  $\phi_n^k(u, v)$  is the length of the shortest path from node  $u \in Ingress$  to  $v \in Egress$  in every path-set  $\rho_n^k$ .

$$\bar{\phi}_s = \frac{1}{N} \left( \sum_{n=1}^N \sum_{k=1}^{K+1} \left( \frac{1}{K} \sum_{(u,v) \in V, v \neq u} \phi_n^k(u, v) \right) \right) \quad (3.6)$$

Table 3.2 summarizes the important notations used in this chapter. The set of paths  $(\rho_n^1, \rho_n^2, \dots, \rho_n^K, \rho_n^{K+1})$  for all the ARs and GW amalgamate to represent one RP.  $\vartheta = \{\theta : \theta = 1, \dots, \Theta\}$  signifies the source and destination pairs of traffic in the network (i.e. *Ingress* and *Egress* points) also called commodities. Case I and Case II were outlined in Section 4.3. In the

**Table 3.2:** Main parameter descriptions

Notation	Description
$\mathcal{V}$	Set of nodes. $\mathcal{V}=\{v : v = 1, \dots, V\}$
$\mathcal{E}$	Set of links. $\mathcal{E}=\{e : e = 1, \dots, E\}$
$\mathcal{N}$	Set of Routing Planes (RPs). $\mathcal{N} : n = 1, \dots, N$
$\mathcal{Z}$	Set of Label-Switched Paths (LSPs). $\mathcal{Z} : z = 1, \dots, Z$
$\mathcal{D}$	Set of demands. $\mathcal{D}=\{d : d = 1, \dots, D\}$
$\mathcal{H}_n^d$	Set of hops. $\mathcal{H}=\{h : h = 1, \dots, H_n^d\}$
$\mathcal{B}$	Number of Users. $\mathcal{B} = \{b : b = 1, \dots, B\}$
$\mathcal{\vartheta}$	Set of commodities. $\mathcal{\vartheta} : \theta = 1, \dots, \Theta$
$\rho_{\mathcal{N}}^{\mathcal{K}}$	Set of paths containing path (i.e. $P_{\mathcal{N}}^{\mathcal{D}}$ ) set
$\mathcal{Q}$	Set of sessions. $\mathcal{Q} = \{q : q = 1, \dots, Q\}$
$\Gamma$	Set of weights for each constraint. ( $\Gamma : \gamma = \gamma_0, \gamma_1, \dots, \gamma_k$ )
$\mathcal{T}$	Set of traffic types $\mathcal{T} = \{t : t = 1, \dots, T\}$
$\Pi^{b,d}$	Traffic rate associated with user $u$ and demand $d$
$m_q$	Additive QoS metrics associated with session $q$
$c_q^t$	QoS constraint of session $q$ associated with traffic type $t$
$\phi_{\Gamma}^t(p_n^d)$	Cost of a path associated with a RP for traffic type $t$
$C(b(p_n^d))$	Link capacity of the least available bandwidth on path $p_n^d$

first case where all the traffic travels through the core, path set  $\rho_n^k$  is represented as follows:

$$\rho_n^k = \left\{ \begin{array}{ll} AR_S \Leftrightarrow GW & : P_n^{d=1} \\ AR_S \Leftrightarrow GW \Leftrightarrow AR_{fi} \neq AR_S & : P_n^{d=2} \\ \vdots & \\ AR_S \Leftrightarrow GW \Leftrightarrow AR_{la} \neq AR_S & : P_n^{d=K} \end{array} \right\} \quad (3.7)$$

In the second case, path-set  $\rho_n^k$  is:

$$\rho_n^k = \left\{ \begin{array}{ll} AR_S \Leftrightarrow GW & : P_n^{d=1} \\ AR_S \Leftrightarrow AR_{fi} \neq AR_S & : P_n^{d=2} \\ \vdots & \\ AR_S \Leftrightarrow AR_{la} \neq AR_S & : P_n^{d=K} \end{array} \right\} \quad (3.8)$$



Where  $\Leftrightarrow$  represents a duplex path through other nodes. The GW-AR pair is reserved in every RP for the case that the desired destination address is located outside of the network and vice versa.  $d = 1$  represents the GW-AR pair in path-set  $\rho_n^1$  and the demand increments up to  $D$  that corresponds to the final *Ingress-Egress* pair in path-set  $\rho_n^{K+1}$ .

Every plane is a subset of the physical topology of the underlying network (i.e. uses all *Ingress*, *Egress* routers and a subset of the transit routers and links). A separate RIB/FIB is maintained for every subset/RP.

### 3.2.5 Offline RP Construction Algorithm

---

**Algorithm 1** Offline Algorithm for Building RPs

---

```

1: procedure RPs-CONSTRUCTION
2:   Build the first InvCap link weights-based RP
3:   if prime objectives (1-4) are met: jump to step 9
else: go to step 4
end if
4:   for  $X = 1 : X_{max}$ 
Derive sets of weights for candidate RPs using the methods in equations (3.8), (3.9) & (3.10)
respectively
end for
5:   Run Dijkstra to create candidate RPs based on the sets
6:   for  $n = 1 : X_{max}$ 
if the candidate RP  $n$  meets objectives 2 & 3 (hence a valid RP)
Record the candidate RP and its hop-length value  $H_n$ 
end if
end for
7:   Find the best RP  $n$  originating from step 6 (three methods) through correlation with the
lowest possible hop-length while ensuring constraints' criteria are met (i.e. equation(3.13))
8:   Go back to step 3 (i.e. the verification process)
9:   RPs are obtained consisting of AR-AR and AR-GW pairs corresponding to Case I or II
10: end procedure

```

---

The pseudo-code of the RP construction algorithm is presented as **Algorithm 2**. Initially, Cisco's InvCap is applied in assigning weights to the links. i.e. for each link  $e \in E$ ,  $w(1, e) = 1/C_e$ . After building the first RP, three heuristic methods are used for computing the link weights 1) Iterative Plane Construction. 2) Link Degree of Involvement 3) Maximum link

degree involvement per demand. The link weight configuration for these methods is obtained as follows:

$$w(n, e) = \frac{1}{C_e} + \frac{1}{n} \sum_{\rho=1}^{n-1} w(\rho, e) + X \cdot \lambda_e(n) \quad (3.9)$$

with  $\forall e \in \mathcal{E}, \forall n \in [1, N-1]$  and with the following:

$$\alpha_e(n) = \begin{cases} 1, & \text{if link } e \text{ is in a path in RP } n-1 ; \\ 0, & \text{otherwise} \end{cases} \quad (3.10)$$

$$\beta_e(n) = \sum_{n=1}^{N-1} \alpha_e(n) \quad (3.11)$$

$$\gamma_e(n) = \max_{d \in \mathcal{D}} \left( \sum_{n=1}^{N-1} \alpha_e^d(n) \right) \quad (3.12)$$

$\alpha_e(n), \beta_e(n), \gamma_e(n)$  represent method 1, method 2 and method 3 respectively as denoted by  $\lambda_e(n)$  in equation 3.7.  $X$  is a multiplicative parameter that is used for the granularity of the methods. The higher the value of  $X$ , the more RPs will be tested.  $X$  ranges from 1 to  $X_{max}$  incremented by 1 with  $X_{max} = \{2; 4; 8; 16; 32; 64\}$ . Method 1 only considers the involvement of a link in RP in  $N-1$ . Method 2 considers the involvement of a link  $e$  in all RP  $n \in [1, N-1]$ . Method 3 is in fact a subset of method 2 where the cost of the most used link  $e$  in RP  $n$  is penalized. Subsequently, correlation between the three contending planes resulting from the aforementioned methods is calculated against the initial RP. The mean correlation is obtained for the resulting RPs from the  $(1 : X_{max})$  loop and the plane with the lowest correlation is picked, having run the Djisktra's algorithm for the different weight-sets. There is a set of rules (i.e. prime objectives) which should be met in the RP construction algorithm: 1) Each link must not be utilized in at least one plane. This is to ensure that  $PDI_e^d$  does not reach beyond its maximum ( $|N-1|$ ) per link. 2) There exists a route for every demand. Routers in between

can be either sources or sinks. 3) The cost between every source-destination pair is minimum for each plane subject to the assigned link weights. 4) Each link is used in at least one plane in order to ensure path diversity.

### 3.2.6 Online Traffic Engineering Mechanism

MPR's online TE approach was initially introduced in [63]. As opposed to the previously considered singular source case, we have adopted a realistic online traffic scenario where both the GW and the ARs can be sources and destinations of traffic simultaneously giving rise to the breakdown of traffic of an internal and external nature. Additionally, we put forward a more complete formulation of MPR's online routing complemented with an optimization framework.

In the network; a set of users is defined as  $\mathcal{B} = \{b : b = 1, \dots, B\}$ .  $\mathcal{T} = \{t : t = 1, \dots, T\}$  indicates the set of traffic types.  $\mathcal{Q} = \{q : q = 1, \dots, Q\}$  represents the set of sessions whereas  $m_q$  signifies the additive QoS metrics associated with every session  $q$ .  $c_q^t$  is defined as the QoS constraint of session  $q$  associated with traffic type  $t$ .  $\Pi^{b,d}$  indicates the traffic rate associated with user  $b$  and demand  $d$ .  $\|\Pi^{b,d}\|_0$  signifies the non-zero non-negative entries of  $\|\Pi^{b,d}\|$ . MPR applies a plane selection policy for each session to ensure a regulated traffic flow in the network. This policy is enforced by the sources (i.e. GW and ARs). In the case of MPR, the cost of RPs are solely determined based on the available bandwidth and if there is more than one RP available, one RP is selected randomly. In the case of QMPR, when a packet arrives at a source, the qualified RPs in terms of bandwidth are first picked out, subsequently the packet's classification gets verified and hence its associated Service Level Requirement (SLR) (i.e. jitter, latency, packet loss) is obtained based on which the plane selection policy is applied. Consequently, RPs that do not meet the required criteria for the concerned traffic class are pruned and the most suitable RP with the lowest cost is selected. At this stage, in case of the existence of more than one RP that meets the QoS criteria, the RP with the highest available bottleneck bandwidth is selected. In the case of both MPR and QMPR, once the qualified RP is selected, the packet is forwarded on the chosen RP followed by the rest of the packets of the

session.

Where  $\gamma_q \in [0, 1]$  is the binary factor used to associate session  $q$  with its QoS requirements.  $b(p_n^d)$  represents the available bandwidth on path  $p_n^d$ . The available bandwidth is calculated by taking into consideration the bottleneck on every path at various instances:

$$b(p_n^d) = \min_{(e_{uv,n}) \in p_n^d} b(e_{uv,n}) \quad (3.13)$$

$$\text{Where: } \{e_{uv} | (u, v) \in \mathcal{V}^2, \forall u \neq v, \forall n \in \mathcal{N}\}$$

$$b(p_n^d) = \{b(e_{uv,n}) | (e_{uv,n}) \in p_n^d, \forall n \in \mathcal{N}\}$$

$\Psi$  is the binary factor which is 1 when any path  $p_n^d$  meets the minimum bottleneck requirement as outlined above.  $Y$  symbolises the binary variable which is equal to 1 in case of both the QoS and bottleneck requirements are met by one or more than one candidate RP hence the one with the highest bottleneck bandwidth is selected.

---

**Algorithm 2** Online Plane Selection Algorithm

---

1: **procedure** POLICY-PS

2: Packet arrives at *Ingress*  $AR_a$ /*GW* destined for *Egress*

3: **If**  $\Pi^{b,d}_0 \leq b(p_n^d)$ , for at least  $n \in \mathcal{N}$  **then**

4: Admit the session

5: Conduct lookup for the associated traffic class  $t \in \tau$

6: Ascertain QoS requirements  $c_q^t$  for traffic class  $t$

7: Remove all RPs in  $\mathcal{N}$  that do not satisfy SLRs for each  $q \in Q$  and retrieve set  $\mathcal{CP}$

8: Calculate cost for each RP

$$\begin{aligned} \Phi_{\Gamma}^t(p_{cp_i}^d) = & \Psi \cdot \sum_{uv \in p_n^d} \sum_{q \in Q} R_{uv p_n^d}^d \left( \frac{m_q(uv)}{c_q^t} \right) \cdot \gamma_q \\ & + Y \cdot \left( \frac{b(p_n^d) - \|\Pi^{b,d}\|_0}{C(b(p_n^d))} \right)^{-1} \end{aligned}$$

9: Select RP  $cp_1$  with the lowest cost  $\Phi_{\Gamma}^t$  for the incoming session given:  $\Phi_{\Gamma}^t(cp_1) \leq \Phi_{\Gamma}^t(cp_2) \leq \dots \leq \Phi_{\Gamma}^t(N - \bar{\mathcal{CP}})$

10: **else** Reject session

11: **end if**

12: **end procedure**

---

### 3.2.7 Performance Evaluation

In this subsection, the performance of different methodologies for fluctuating internal/external traffic distribution under different scenarios (i.e. Case I & Case II as outlined in subsection 3.2.1) are briefly discussed and analysed in terms of various metrics., summarising them from more detailed study presented in [17] and extracted in Appendix B. This study corresponds to an analysis under a realistic traffic scenarios with two structural cases that are reflective of the architectural evolution of access networks as discussed in section 3.2.1. In addition to the simulation scenarios discussed in subsection 3.2.3, all the topologies listed in Table 3.1 are tested using Matlab modelling that runs the offline algorithm and produces input of RPs for the online algorithm, which is then conducted in the extensive network level simulations using the NS2 modelling tool. Traffic is gradually intensified in the network via insertions at Gateway/Ingress routers until the simulation terminates at the 12th second, after network undergoing a heavily congestion between 11th and 12th seconds.

#### Performance Metrics

Table 3.3 and Table 3.4 represent the achieved network's mean throughput (Mb/s) under varying traffic percentages. As observed, the achieved mean throughput is generally higher in Case II for different routing strategies as compared with Case I. This can be explained by the higher path diversity available in Case II resulting in larger amount of data being delivered. The MPR-based methods outperform OSPF/InvCap as traffic can be split over several paths in the case of MPR, leading to improved load balancing in the network and increased packet delivery correspondingly. The average of the overall achieved throughput for both cases has declined with the rise in the internal traffic distribution aligned with the surge in blocking. Additionally, it can be observed that throughput has risen in line with the increase in meshing as the session blocking rate has declined correspondingly for both topology-sets. It can be also observed that a generally higher throughput has been achieved in the case of the second topology-set where more traffic gets injected into the network.

**Table 3.3:** Throughput (Mb/s) for the first topology

Traffic	OSPF/InvCap				MPR				QMPR			
(%)	Case I		Case II		Case I		Case II		Case I		Case II	
	$T_1M_1$	$T_1M_2$	$T_1M_1$	$T_1M_2$	$T_1M_1$	$T_1M_2$	$T_1M_1$	$T_1M_2$	$T_1M_1$	$T_1M_2$	$T_1M_1$	$T_1M_2$
10	30.01	30.01	26.86	26.74	40.37	50.28	51.82	58.14	40.25	48.30	48.78	55.84
20	29.92	29.92	26.52	26.45	40.35	50.21	51.25	57.62	40.2	48.16	48.21	55.82
30	29.92	29.92	26.49	26.39	40.48	50.50	50.87	57.60	40.29	48.1	47.92	55.74
40	29.88	29.88	26.44	26.37	40.26	49.91	50.39	57.40	40.17	47.93	47.54	55.61
50	29.82	29.82	26.4	26.3	40.18	49.81	50.12	57.03	40.16	47.39	47.11	54.81
60	29.77	29.77	26.35	26.28	40.12	49.49	49.15	56.43	40.07	46.9	48.49	54.62
70	29.61	29.61	26.32	26.22	40.9	49.38	49.06	56.53	40.03	46.92	46.82	54.47
80	29.59	29.59	26.29	26.18	40.42	49.26	48.73	56.11	40	46.51	46.68	54.22
90	29.47	29.47	26.18	26.12	40.29	48.8	48.65	56.04	39.95	46.19	46.57	54.03

**Table 3.4:** Throughput (Mb/s) for the second topology

Traffic	OSPF/InvCap				MPR				QMPR			
(%)	Case I		Case II		Case I		Case II		Case I		Case II	
	$T_2M_1$	$T_2M_2$	$T_2M_1$	$T_2M_2$	$T_2M_1$	$T_2M_2$	$T_2M_1$	$T_2M_2$	$T_2M_1$	$T_2M_2$	$T_2M_1$	$T_2M_2$
10	31.29	31.29	47.44	47.44	47.44	52.52	102.2	120	42.84	48.52	97.39	115
20	31.26	31.26	47.15	47.15	47.15	52.53	102.1	120.3	42.45	48.53	96.34	115
30	31.15	31.15	47.02	47.02	46.18	52.43	101.1	120.8	42.18	48.43	97.84	115.7
40	30.30	30.30	46.51	46.51	46.63	51.61	100.5	120.1	42.51	47.61	96.35	114
50	30.08	30.08	46.24	46.24	45.24	51.46	100.5	119.5	42.14	46.63	97.36	114.4
60	30.18	30.18	46.44	46.44	45.39	50.54	100.4	118.7	41.44	46.54	96.19	113.3
70	30.19	30.19	46.14	46.14	45.24	50.70	100.2	116.2	41.44	46.21	96.65	113.1
80	30.07	30.07	45.21	45.21	45.21	50.34	99.83	114.9	41.21	44.54	96.14	112.6
90	30.04	30.04	44.08	44.08	45.08	50.15	99.45	113.2	41.08	42.15	96.61	112.3

Furthermore, it was shown in [17] that MPR and Case II outperform their counterpart methods and strategies in terms of other network metrics (i.e. Delay, Blocking Rate, Packet Loss Rate, Maximum Link Utilization) under fluctuating internal/external traffic distribution. A summary of the findings for other key performance criteria/metrics is as follows:

a) Blocking Rate: since the traffic insertion conditions included checking the availability of resources before admitting sessions/packets into the network, expected higher blocking situations occurred in heavily congested conditions for lesser meshed topologies and with more careful control of routing resources as in the case of QMPR. Similarly, for Case II there is less blocking as there is a more distributed use of the networks routing resources.

b) Packet Loss Rate: marked by percentages of packets losses in routers queues, expectedly, with Case II and when meshing was increased, packet loss rate decreased due to more routing resources. Furthermore, specific findings included: for QMPR, losses are lower as packets are more carefully inserted into the network; when internal traffic between routers increases, losses also increase hinting at lower data rates in links closer to the edge of the network that then become more heavily utilised; and, when the number of traffic sources increase in the network, despite the network being larger in size as for the second set of topologies, packet losses escalate as the network gets more heavily loaded with traffic.

c) Delay: two major conclusions most appropriately signify the performance related to delay: a) MPR induces extra (hop-count-based) delay as the packet routes in the network are not always shortest-hop; b) delays due to deviations from the shortest-hops need not be critical, due to delays being dependent on residual capacity in the network that is augmented with MPRs path diversity, and, delays incurred in the IP access networks can be negligible to delays in the outside Internet. In accordance, the results show that when increasing meshing and for packet distributions in Case II, delays lower.

d) Maximum Link Utilisation (MLU): expectedly, when meshing is increased as in Case II, MLU decreases as there is more routing resources available in the network.

Specifically, in addition to the demonstration of MPR-based methods' superiority over

legacy OSPF/InvCap methods, it was shown that the flat-IP based design concept (case II) outperforms the hierarchical-based concept (case I). Moreover, it was demonstrated that the surge in the internal traffic ratio would result in performance degradation under both network architecture design concepts generally improving with more meshing in the networks.

### **3.3 A novel reliable Multi-path routing scheme for Tactile-oriented Internet traffic**

Presently, the Internet supports voice and data communications in addition to multimedia services such as audio and video. In the last few years, many scientists have proposed an Internet generation that will support haptics communication in addition to voice and data communications. Correspondingly, the Tactile Internet must enable haptics communication [95] as a major application and facilitate the underlying medium for transporting such applications. This Internet dimension has the potential to benefit our society by facilitating the introduction of new technologies and applications that will enhance our standards of living.

It is envisioned that Tactile Internet communication would be feasible only in scoped and/or reasonable communication distances. This is because of the associated stringent QoS criteria making it hard to manage over the ranges of Internet networks which can be traversed by the packets with different QoS flow criteria. To this end, the current research concentrates on scoped network(s), dedicated transmission lines for long haul communications or single administrative domains (namely access networks) where a routing optimization mechanism can be applied.

#### **3.3.1 Tactile Internet**

The Internet dimension associated with Haptics is now known as the Tactile Internet, a term first introduced by G. P. Fettweis in 2014 [96, 97]. Tactile Internet corresponds to an ultra-reliable and ultra-responsive connectivity which enables physical Haptics experiences re-

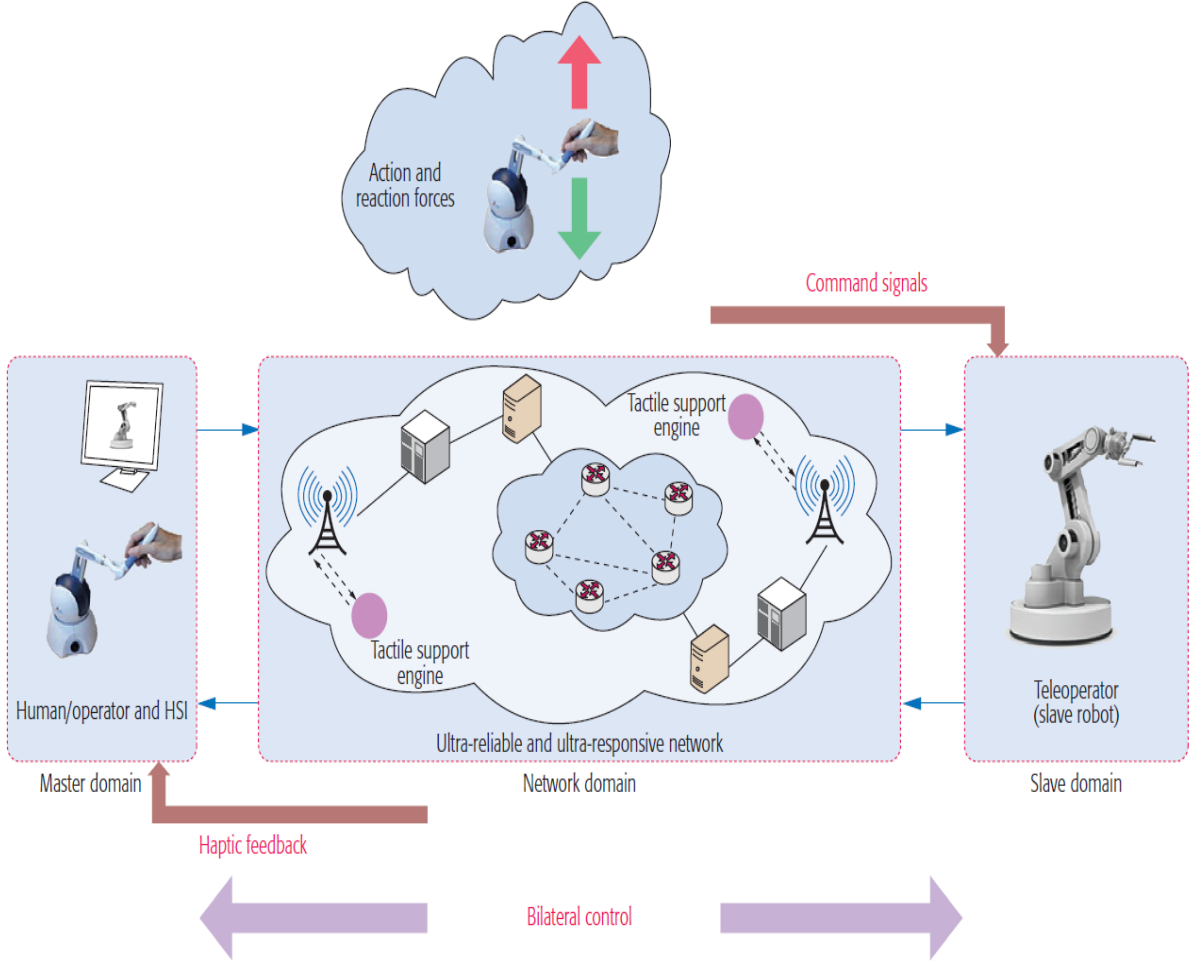


motely through machine interfaces, augmenting a new dimension to human to machine interactions [98]. The International Telecommunication Union (ITU) has defined the technical specifications of Tactile Internet [99] with the aim of revolutionizing the Machine to Machine' (M2M) and 'Human-to-Machine' (H2M) communications [15]. Additionally, vendors have envisioned and put forward some likely benefits of this new Internet generation to be exploited [96, 99, 100]. A market analysis has predicted that the likely overall market value for this new Internet dimension could be beyond 20 trillion dollars on a global scale, amounting to approximately 20 percent of the global GDP [101].

The thinning of the core achieved by functional decomposition and the delegation of some responsibilities to access, is proposed by authors in [102] in order to facilitate the necessary QoS and security for tactile applications. The following three distinct domains represent the end-to-end architecture for Tactile Internet providing the medium for Haptics transport: the master domain, the network domain, and the slave domain illustrated in Figure 3.4 [98]. The network domain represents the medium for end to end communication between the master domain and the slave domain, (kinesthetically connecting humans to the far environment). In an optimum case, the operator would be entirely immersed in the remote environment.

Several studies have been conducted on Tactile Internet that are not fully nurtured and do not concentrate a single Internet aspect, instead, a collection of proposals and thinking towards addressing some general needs for Tactile Internet. Haptics motion and force prediction techniques have also been investigated in [103]. Such mechanisms plan to reduce networks' effects such as delay, jitter and packet loss [104]. SDN was adapted to facilitate deterministic tactile packets' transmission in core networks [105]. Authors in [106] state that packet re-transmission and latency could be relaxed majorly through the amalgamation of network coding and SDN. However, the aforementioned research do not look into the potential for path diversity based multi-path routing for large scale network topologies. We adapt multi-path routing optimization in this research with the aim of expediting routing characteristics for certain traffic types.

In the following sections, we briefly discuss about multi-path routing applications in Hap-



**Figure 3.4:** Functional architecture of the Tactile Internet providing the medium for Haptic transport

tics communication followed by the introduction of a novel routing policy that accommodates for Tactile-oriented Internet traffic with the backdrop of the stringent QoS requirements.

### 3.3.2 Multi-path Routing Applications in Haptics Communication

We aim to ratify tactile's support in scoped Internet networks by considering three specific criteria (i.e. delay, jitter and packet loss) in addition to ensuring bandwidth availability as a practical necessity with equal bearing. Multi-path routing which enables path diversity is significant for expediting routing characteristics. The proposed policy build upon MPR's routing optimization mechanism for access networks (i.e. Intra-domain routing in single scoped administrative domains). MPR has been remodelled to facilitate a reliable communication for

Tactile packets by installing two types of queues in routers for priority and non-priority traffic respectively.

In case of MPR, as discussed previously, the availability of multiple routing paths for each *source-destination* (i.e. *Ingress-Egress*) pair in the network is ensured. MPR with extensions in routers' queues (i.e. resembling a coupling with DiffServ approaches) is an attractive routing solution for haptics communication in scoped access networks as it allows a network wide efficient differentiation of routing resources. MPR has already proven to achieve performance gains as compared with MPLS and OSPF considering the whole network and a notable number of key performance criteria as laid out in [107]. In addition, the online and offline segregation of algorithms in MPR enables pre-planned and extremely responsive adaptations to various traffic QoS criteria, rendering it a more adaptable and faster solution than conventional IntServ schemes and native SDN approaches which incur route configuration delays that could be intolerable in the case of Tactile applications.

### 3.3.3 Tactile-Aware Policy

The proposed Tactile aware TE algorithm is based on MPR's online TE policy. MPR's approach has been remodeled to allow for the evolutionary Tactile Internet. Correspondingly; we have put forward two types of queues and a new plane selection policy.

Tactile Aware Policy (TAP) segregates the network into a hierarchy in the presence of traffic of both downlink and uplink nature. Every time a packet arrives at the *Ingress*, it is checked whether it belongs to a new session. If the packet that arrives at the *Ingress* does not belong to any existing sessions, then the *Ingress* node should apply the following principles. Firstly, the *Ingress* has to check if there is enough bandwidth in order to support the new session. In the case where there exist enough free resources, the session will be admitted. However, if there are not enough available resources to be used the packet will be dropped and the session will be rejected. When the session has been admitted, MPR's online algorithm will be used in order to route the packet. At this point it is worth mentioning that when a route has been used to

route a packet then all the packets that belong to the same session will follow the same route to preserve the same transport conditions. In the following paragraphs TAP's functionalities are described in detail.

Firstly, when a Tactile packet arrives at the *Ingress*, a duplicate is generated. The initial packet will be routed by using the best path in terms of delay and the duplicate packet will be routed on the second best path in terms of delay. The main idea behind the generation of the duplicate packet is to increase the communications reliability which is vital in case of Tactile traffic. The duplicate packet generation helps in reducing the packet loss that is one of the main constraints that needs to be dealt with. When the initial packet has been dropped, there is a possibility that it can be restored by the duplicate. Based on TAP, the packet that arrives first at the *Egress* is considered to be valid. In case of both packets having been delivered successfully, the one that has arrived second will be dropped.

Another major constraint of the Tactile Internet is that the round trip time must not exceed the threshold of  $1ms$ . In order to achieve this, we classify the packets into two classes. The first class (i.e. priority class) represents the Tactile packets and the second class represents all the other types of packets (i.e., VoIP, Web etc.). To this end; we assume that each router has two queues. One for the priority class packets and one for the packets that belong to the other classes. The router's scheduler will try to serve the packets from the first queue. When the priority queue is empty or the non-priority queue has been used for a long period, it will start serving packets from the non priority queue. However, in the case where a priority packet arrives at an empty priority queue while the scheduler is serving a non-priority packet, the priority packet has to wait until the scheduler pushes non-priority packet to the link. By following this strategy, the queueing delay will be reduced significantly leading to the overall reduction of delay. Finally, priority packets are inserted before the non-priority in case the queue is full of non-priority and priority packets arriving at the queue. The main reason behind that is we aim to avoid starvation of the non-priority class packets and at the same time provide high priority to the priority class packets. The TAP policy is summarized in Algorithm 5 (

Appendix C).

### 3.3.4 Analytical Evaluation

The results that were presented in [108] in terms of the most critical metrics (i.e. delay, jitter, throughput and packet loss) pertain to Haptics traffic performance. Two different access network topologies of different meshings have been investigated under a realistic traffic scenario with a varying range of traffic classes. Correspondingly, it was allowed for different types of traffic (i.e. including Tactile) to flow through our topologies in order to evaluate the performance of the TAP algorithm under a realistic scenario. It has been shown that the TAP policy performs extremely well for different levels of congestion (outperforming OSPF and performing not far from the optimum). Moreover, as TAP is based on MPR that is a purely IP traffic engineering approach, it would render negligible communication overhead in the network. Generally, it has also become apparent that shortest-path solutions such as OSPF can not be used in order to handle Haptic communications in typical Internet network topologies.

The conducted evaluation of MPR for supporting the tactile traffic primarily offers a thorough insight into possibilities of both the multipath routing and of using the whole of the network topology for traffic distributions. In accordance, the results show how close the MPR-TAP TE comes to an optimal performance in the given network conditions that have been setup to highlight the routing and queuing delays (e.g. transmissions, propagations and processing delay were set to theoretical or very idealist values). In fact, with a careful selection of the online method, as done using the MPR online algorithm and TAP, packet distributions can selectively exploit greater routing resources and flexibly meet the appropriate delay and jitter margins without enforcing the shortest path principle. The variations in meeting the criteria for tactile traffic can be seen in the offsets compared to the optimal case as well as the very basic routing setup via OSFP. It is also evident that for all the evaluation criteria (i.e. packet loss rate, delay and jitter, assuming bandwidth is met as well) the second topology used in the evaluations, which has more links per router (i.e. higher degree of meshing) comparably achieves

better results as more path diversity is available and ensured via MPRs multipath routing and its offline algorithm.

As expected in the simulation scenarios, packet delivery disruptions occur due to finite queue sizes and buffer overflows. M/M/1 queues were used to focus the experiment on routing effects and apply the most elemental conditions with the exception of having the two queues run for priority and non-priority traffic. Otherwise it would not be realistic to keep the tactile traffic criteria margins for cases where links and the network become reasonably loaded with traffic. In addition, duplication of tactile traffic packets, as part of TAP, has enabled tactile traffic to be supported in cases of very high link utilisation right until the 11th second of the simulations when network achieves almost 100% link utilisation in significant parts of the topologies. In fact, in the case of OSPF it was evident that already at around 50% link utilisation (assuming traffic gradually reaches 100% by the 11th second, hence 50% link utilisation approximately between 5th and 6th second) the queues become overloaded with packets due to lack of diversity and use of a single path per each Ingress-Egress pair in OSPF. MPR multipath routing thus allows for an extension of the moment of a packet loss during simulations as duplicated packets traverse different paths hence reduce the chance of losing a packet in the network. In addition, due to introducing the priority and non-priority queue packet management (20% traffic was tactile, i.e. priority) even during high link utilisation, which occurs towards the end of simulation times, packet losses for the tactile sessions were negligible due to duplications of sessions: for T1M1 topology only 13 packets needed to be restored while for T1M2 topology only 8 packets needed to be restored. The same maintenance of smooth packet delivery was reflected in the delays measured that have maintained desired margins throughout the simulations due to duplications where delayed packets were compensated for by the packet duplicates. Likewise, the jitter has continued to be almost constant with a slight linear increase, in case of OSPF being greater due to fuller and more overloaded queues.

The simulation have convincingly shown that with some queue management alterations and packet duplications, multi-path routing solely achieves great improvements in the margins

for satisfying the stringent QoS requirements of the tactile traffic. Evidently, this occurs at the expense of added overhead of packet duplications and it is a topic for further evaluations and analysis, perhaps, combinations with some other QoS schemes such as IntServ or DiffServ. Decisions on supporting tactile traffic are to be left to INPs/network operations, considering for example, scales of deployments and commercial considerations, but, it becomes tangible and evident that a considerable increase in access networks ability and confidence in supporting the tactile traffic requirements can be provided for by the multi-path routing and the MPR TE scheme.

### **3.4 Summary**

In this chapter, IP TE-based MPR has been remodelled to suit the future all-IP access network structures by utilising the entire network's routing resources. The evolution of network architecture designs as reflected in the trend towards a flat-IP structure, along with the rise of IP-based real-time applications call for a consistent routing paradigm. MPR augments the constrained shortest-path routing paradigm allowing the network to deploy path diversity by concurrently maintaining several independent logical topologies. The resultant diversity allows for network wide load balancing and is suited to various topological configurations. Being facilitated by multiple OSPF topology instances in networks that are controlled by offline and online algorithms, MPR achieves path diversity with minimal extra protocol overhead. Two cases that are reflective of the evolution in the network architecture design have been investigated in terms of various metrics under fluctuating internal/external traffic distributions to emulate a comprehensive realistic set of traffic scenarios that facilitates a thorough performance evaluation. In addition to the demonstration of MPR-based methods' superiority over legacy OSPF/InvCap methods, it has been shown that the flat-IP based design concept (Case II) outperforms the hierarchical-based concept (Case I). Additionally, the surge in the internal traffic ratio has resulted in performance degradation under both network architecture design concepts

but has generally improved with more meshing in the networks. Moreover, a novel reliable MPR-based routing scheme was laid out and discussed in consideration of the strict Tactile Internet's characteristics and requirements. It was argued that the proposed policy outperforms intra-domain routing protocols namely OSPF and performs near-optimally.

In the next chapter, a novel Minimum-Set Cover RP construction strategy for randomly shaped (i.e. random graphs) IP access networks will be proposed. To this end, the offline TE problem (analytical model) of building multiple planes (i.e. path-sets) will be expanded and presented as being the generalization of the minimum set cover problem accordingly. This approach adopts a dynamic minimum set-cover based cost function in order to construct a diverse set of RPs while also considering capacity. The effectiveness of the approach will be demonstrated for a wide-ranging set of randomly generated graphs of different sparseness levels where the legacy MPR's TE mechanism is redundant.



# 4

## **A Novel Minimum Set Cover Routing Plane Construction Approach for Randomly Shaped IP Access Networks**

### **4.1 Introduction**

In the previous chapter, MPR's offline and online algorithms were extended to reflect the changing architecture of access networks while integrating various associated practical aspects in the investigation. All the presented simulation results verified MPR's performance potential and its superiority over its rival strategies in all-IP access networks. Tactile Internet was also accommodated for, as another practical application of MPR. To this end, a novel reliable MPR-based routing scheme was outlined in consideration of the specific Tactile Internet's characteristics and requirements. In this chapter, a novel minimum set cover routing plane construction scheme for randomly shaped access network structures is proposed.

The expected mutable nature of future access network structures calls for network providers to adapt accordingly in order to facilitate loss free networks supported with the developing IP infrastructure. To this end, a routing optimization mechanism applicable to randomly shaped

all-IP access networks must be developed. In this chapter, Multi-Plane Routing (MPR) that consolidates various aspects in all-IP infrastructure as a whole is redesigned and reformulated to provide a comprehensive solution in consideration of the randomness of future access networks. We focus on the offline TE aspect (network planning phase) of building multiple planes (i.e. path-sets) which has the physical topology with associated randomly allocated link capacities as the input (depending on link's level). The suggested approach expands upon MPR which is not suited to random graphs and deployment scenarios of topologies that are expected in emerging dense topological layouts of backhaul networking as explained in Chapter 3. To this end, the topology independent RP construction is redesigned and reformulated to suit the randomly shaped access networks with the aim of achieving maximum path diversity and use of entire routing resources. We prove the offline Routing Plane (RP) construction problem as being the generalization of the Minimum Set Cover (MSC) problem which is NP and also NP-complete. To this end, a novel MSC-based paths-diverse offline TE algorithm which is comprehensively applicable to randomly shaped access network structures. Our simulation results demonstrate the constructed RPs for complex random networks of different sizes and sparseness (i.e. meshing) extensively. Hence, the comprehensive applicability of our novel approach is verified. The effectiveness of our paths diverse approach for large-scale random topologies is also demonstrated which sets our approach apart from the legacy MPRs RP construction method. Moreover, a new optimization framework along with a dynamic cost function is proposed (considering capacity projections and correlation of paths) that formally describe our novel offline TE mechanism for future randomly shaped wireless IP access networks.

## 4.2 Outline and Contributions

In consideration of the uncertainties regarding the future all-IP access networks' structure and given the disparately shaped existing access structures, a routing optimization method applicable to randomly shaped IP access networks must be developed. Such an approach aims

to provide a comprehensive solution for future access networks. MPR's legacy offline TE approach [16] that aims to achieve full path diversity suffers from deficiencies and limitations in terms of applicability to randomly shaped access networks and it is limited to meshed tree topologies that follow essential configuration of networks. This is because of the algorithm's arbitrary RP construction method as explained the previous Chapter, is built by varying link weights that render paths via the OSPF path construction Dijkstra algorithm. In wilder scenarios of larger, randomly configured IP access network topologies this method contains significant constraints that can prove inapplicable in case of random graphs as input to the algorithm which are likely to occur in practical scenarios of network installations and configurations (e.g. HetNets [20], core/backhaul TE for 5G [67]). In this work, we redevelop the offline TE aspect (network planning phase) of MPR which has the physical topology with associated randomly allocated link capacities as the input (depending on link's level). Under the new scenario, the topology independent RP construction is redesigned and reformulated to suit the randomly shaped access networks with the aim of achieving maximum path diversity and use of entire routing resources.

In this chapter, a novel MSC-based paths-diverse routing optimization approach for future all-IP wireless access networks with random topological structure is proposed. This protocol expands upon MPR which is not suited to random graphs. This study considers a comprehensive routing scheme applicable to randomly shaped access networks with different levels of meshing. It is notable that MPR is based on a link weight penalization-based cost heuristic whereas MSC explicitly compares paths by adapting a novel dynamic cost function with correlation and link capacity elements followed by reverse engineered Dijkstra link weight assignment for every path-set corresponding to every RP. To the best of our knowledge, the study of such a comprehensive TE mechanism which is applicable to randomly shaped access networks is absent in literature. We propose a new optimization framework (considering capacity and correlation of paths) that formally describes our novel offline TE mechanism. Furthermore, we revisit the multi-topology (i.e. RPs) construction problem in intra-domain networks.

To this end, we prove the offline RP construction problem as being the generalization of the Minimum Set Cover (MSC) problem which is NP-complete. Hence, the adoption of heuristics is justified. Correspondingly, a dynamic MSC-based cost function is formulated to construct a diverse set of routing planes in a random access network followed by the proposition of algorithms for building a finite set of possible RPS. Consequently, a novel comprehensive dynamic MSC-based RP construction algorithm is proposed. The possibility for existence of more than one gateway in a given access network is also introduced.

## 4.3 Analytical Model

In this section, we revisit the problem of building multiple planes (i.e. path-sets) explicitly and formulate the associated optimization problem accordingly.

### 4.3.1 Problem Formulation

The main objectives in our multiple plane construction approach are initially set out as follows. Given an underlying physical network topology, a set of *disjoint* routing planes (RPs) is to be extracted such that each RP would end up with a path between every source-destination pair and every link in the network *would appear at least once* in the RP-set. Specifically, the disjoint requirement is imposed so as to ensure maximum diversity across the RP-set. Meanwhile, the criterion of a link appearing at least once, ensures that all the links in the network would be used (i.e. the whole topology would be utilized). In conjunction, these constraints are aimed at achieving maximum path diversity across the RP-set over the state-of-the art approaches that will be introduced in the following sections. In addition to these constraints, it may be also desirable to impose the usual constraints commonly imposed in TE, such as least cost paths, maximum capacity constraints and so on. Therefore, we can precisely summarize our prime objectives as follows:

**Table 4.1:** Main Parameter Descriptions

Notation	Description
$\mathcal{V}$	Set of nodes. $\mathcal{V}=\{v : v = 1, \dots, V\}$
$\mathcal{E}$	Set of links. $\mathcal{E}=\{e : e = 1, \dots, E\}$
$\mathcal{P}$	Set of Routing Planes (RPs). $\mathcal{P} : p = 1, \dots, P$
$\mathcal{Z}$	Set of Label-Switched Paths (LSPs). $\mathcal{Z} : z = 1, \dots, Z$
$F(C_e)$	Monotonically increasing function of capacity
$\mathcal{S}$	Sets. $\mathcal{S}=\{s : s = 1, \dots, S\}$
$w(e)$	The weight associated with each link
$\vartheta$	Set of commodities. $\vartheta : \theta = 1, \dots, \Theta$
$\rho$	Correlation factor
$cs_i$	Dynamic cost associated with each RP
$\mathcal{R}_{\mathcal{L}}$	set of those planes that have already been selected
$L$	Graph Laplacian
$\mathcal{T}$	Set of traffic types $\mathcal{T} = \{t : t = 1, \dots, T\}$
$C$	Set cover
$t$	Greedy iteration
$f_t(S_i)$	Dynamic cost function associated with each RP
$C(r_p^\theta)$	Link capacity of the least available bandwidth on path $r_p^\theta$

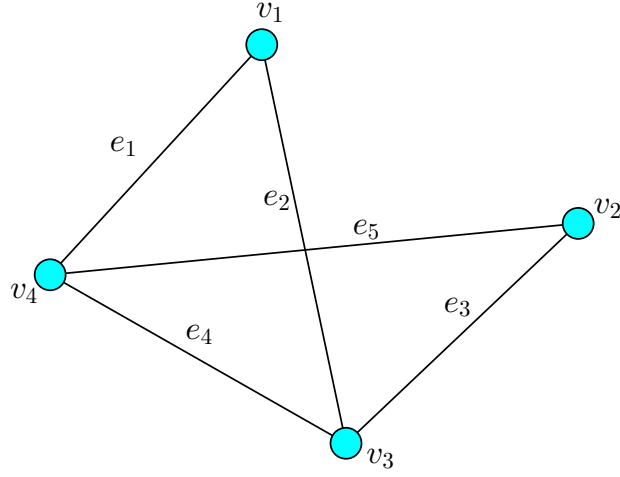
**Problem 1.** *Given a network represented by an underlying arbitrary graph topology  $G = (\mathcal{V}, \mathcal{E})$ , with the vertex and edge sets  $\mathcal{V}$  and  $\mathcal{E}$  respectively, retrieve a set  $\mathcal{R} = \{R_p\}_{p=1}^P$  of  $|\mathcal{R}| = P$  routing planes, such that the following properties hold:*

- (a) *Each RP constructed contains a valid path for every source-destination pair in the underlying network  $G$ ; in other words for every  $p = 1, 2, \dots, P$ ,  $R_p \in \mathcal{R}$  should be a connected subgraph <sup>\*</sup> of  $G$  (i.e. an instance of OSPF).*
- (b) *Ideally, every link in the underlying network topology should appear in only one of the constructed routing planes. Denote the  $p$ -th RP as the subgraph  $R_p = (\mathcal{V}_p, \mathcal{E}_p)$  with vertex and edge sets  $\mathcal{V}_p$  and  $\mathcal{E}_p$  respectively, then if  $e \in \mathcal{E}$  then there exists a  $p$  such that  $e \in \mathcal{E}_p$ . This also implies that the union  $\bigcup_{p=1}^P R_p = G$ .*
- (c) *All the selected RPs are completely different from each other. This means that for each  $p, q = 1, 2, \dots, P$ , if  $e_p \in \mathcal{E}_p$  and  $e_q \in \mathcal{E}_q$ , it follows that  $\mathcal{E}_p \cap \mathcal{E}_q = \{\emptyset\}$  if  $p \neq q$  whilst  $\mathcal{E}_p \cap \mathcal{E}_q = \mathcal{E}_p \cup \mathcal{E}_q = \mathcal{E}_p$  for  $p = q$ .*
- (d) *Finally, the cost, as prescribed by some function  $f$  (e.g. of edge weights or their capacities) is optimal between every source-destination pair for each routing plane.*

It is not difficult to see that the constraints, specifically (b) and (c) in Problem 1, are very restrictive and might even mean that no feasible solution would exist to the problem in some proverbial cases. In Figure 4.1 (representing a full-duplex example where all nodes are Ingress/Egress), a connected subgraph of  $G$  is  $R_1 = (\mathcal{V}, \{e_1, e_2, e_3\})$ , however it is no longer possible to construct another subgraph of  $G$  that simultaneously satisfies (b) and (c). In particular the only unused links are  $e_4$  and  $e_5$ , but the subgraph  $R_2 = (\mathcal{V}, \{e_4, e_5\})$  is not connected hence not representing a valid routing plane as it does not encompass all the *Ingress – Egress* pairs. To avoid such scenarios, it makes sense to relax the restriction (c) such that the links could be reused. However, despite this relaxation, we would still aim for the subgraphs to be

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<sup>\*</sup>in terms of connectivity between all the ingress-egress pairs of vertices, with the possibility of the transit routers in  $G$  not being included



**Figure 4.1:** An underlying network topology  $G$  with four vertices and five edges.

as different as possible; sticking with the same example, this means we may prefer to choose  $R_2 = (\mathcal{V}, \{e_1, e_4, e_5\})$  instead of  $R_2 = (\mathcal{V}, \{e_1, e_2, e_5\})$  given the choice  $R_1$  considering the latter reuses two links instead of one. In light of this, we would need to define a suitable graph similarity metric to enable us to compare any pair of graphs and determine precisely how similar or dissimilar they are. Hence with this similarity metric, a penalty for reusing links in our optimization problem can be properly imposed. To this end, we provide definitions in the following section.

### 4.3.2 Measuring the similarity of subgraphs (planes)

**Definition 1** (Graph Correlation metric). *The graph correlation metric is a measure of similarity between a pair of graphs. This metric is defined herein to be the total number of different links present between the graphs, normalized by the number of edges in the graph containing the highest number of edges. Mathematically, let  $R_p = (\mathcal{V}_p, \mathcal{E}_p)$  and  $R_q = (\mathcal{V}_q, \mathcal{E}_q)$  then it follows that:*

$$\rho(G_p, G_q) = \frac{|\mathcal{E}_p \cap \mathcal{E}_q|}{\max(|\mathcal{E}_p|, |\mathcal{E}_q|)} \quad (4.1)$$

It is easy to see that  $\rho(G_p, G_q) \geq 0$ , in fact  $\rho(G_p, G_q) \in [0, 1]$  with  $\rho(G_p, G_q) = 1$  if and only if  $G_p = G_q$ ; whilst  $\rho(G_p, G_q) = 0$  if  $\mathcal{E}_p \cap \mathcal{E}_q = \{\emptyset\}$  (as a technicality, to avoid dividing by zero, we may assume that at least either  $\mathcal{E}_p$  or  $\mathcal{E}_q$  is nonempty). In addition, we can also deduce that if  $\rho(G_p, G_q) = 0$ , then for any two nodes in  $G_p$  joined by a single edge, the same pair of nodes in  $G_q$  will be joined by a path with at least two different edges.

Furthermore, from equation Definition 1, we can also deduce an expression for  $\rho(G_p, G_q)$  in terms of their corresponding adjacency matrices i.e.  $\mathbf{A}_p, \mathbf{A}_q \in \mathbb{R}^{N \times N}$  (where  $N = |\mathcal{V}|$  is the number of nodes in the network):<sup>†</sup>

$$\rho(G_p, G_q) = \frac{\mathbf{1}^\top (\mathbf{A}_p \odot \mathbf{A}_q) \mathbf{1}}{\max(\mathbf{1}^\top \mathbf{A}_p \mathbf{1}, \mathbf{1}^\top \mathbf{A}_q \mathbf{1})}, \quad (4.2)$$

where  $\odot$  represents the element-wise (Hadamard) product between the two matrices and  $\mathbf{1} \in \mathbb{R}^N$  is a vector with all its entries being equal to unity.

### 4.3.3 Enforcing diversity by minimizing link presence

Since it has been allowed for the links to be reused across multiple RPs (as a result of our relaxation in section 4.3.1), different restrictions must be applied to this re-usage in order to minimize the chance of a link being used in all RPs. The following definitions represent the measures of diversity:

**Definition 2** (Link Presence). *The link presence is a function with a binary output indicating whether or not a link  $e \in \mathcal{E}$  is used in the routing plane  $R_p$ . Denoting it as  $LP: \mathcal{E} \times \mathcal{R} \rightarrow \{0, 1\}$ ,*

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<sup>†</sup>Which can be more useful when implementing matlab based algorithms.



then:

$$LP(e, R_p) = \begin{cases} 1, & \text{if } e \in R_p \\ 0, & \text{otherwise} \end{cases}. \quad (4.3)$$

**Definition 3** (Full Link Presence). *The full link presence indicates the appearance of an edge in all routing planes; defined mathematically as:*

$$FLP(e) = \begin{cases} 1, & \text{if } \sum_{p=1}^P LP(e, R_p) = P \\ 0, & \text{otherwise} \end{cases}. \quad (4.4)$$

### 4.3.4 The optimization problem

In this subsection, Problem Problem 1 and its relaxed version as presented previously will be formally described in terms of the relevant optimization problems consecutively (i.e. 4.6 & 4.7).

The initial objective of our problem is to maximize the projected capacity<sup>‡</sup> for each routing plane that is to be constructed. Let  $\mathbf{C}$  be the capacity matrix, which we assume to be normalized so that its entries only take on values between 0 and 1, also denote by  $C_e \in [0, 1]$  the capacity of the edge  $e$  and by  $r_m^{l,k}$  the  $m$ -th route (which is simply an ordered sequence of edges) between the *Ingress* – *Egress* pair  $l$  and  $k$ , so that the collection of all possible routes between  $l$  and  $k$  is  $\{r_m^{l,k}\}_{m=1}^{M_{l,k}}$ . With these definitions, we can state our main objectives:

1. In the path linking the nodes  $(l, k)$  (i.e. *Ingress* - *Egress*), the link with the smallest available capacity could be the source of the potential bottleneck, hence we aim to alleviate such projected bottleneck in a given path.

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<sup>‡</sup>We could easily replace this with some other well defined associated cost function, that may include in addition to the capacity, path length and so on.

$\tilde{C}(r_p^\theta)$  represents the available capacity (i.e. the residual capacity that could potentially cause bottleneck) on path  $r_p^\theta$  that is associated with plane  $p$  and commodity  $\theta$ . The available bandwidth is calculated by taking into consideration the bottleneck on every path at various instances:

$$\tilde{C}(r_p^\theta) = \min_{(e_{lk,p}) \in r_p^\theta} C(e_{lk,p}) \quad (4.5)$$

Where:  $\{e_{lk}|(l,k) \in \mathcal{V}^2, \forall l \neq k, \forall R_p \in \mathcal{R}\}$

2. We aim to maximize the minimum projected residual capacity (potential bottleneck) considering all pairs of nodes, i.e. for all  $l, k = 1, 2, \dots, N$  and  $l \neq k$ ; across all the candidate  $P$  routing planes (i.e paths).

It is notable that we assume the existence of a composed set of RPs (i.e.  $\mathcal{S}$ , the derivation of which will be presented in section 4.4) in our optimization problem formulations as follows. Correspondingly, the objective of selecting the most fitting plane-set (as laid out in Problem 1) can be stated in terms of the following optimization problem:

$$\begin{aligned} & \underset{\mathcal{R}=\{R_p\}_{p=1}^P}{\text{maximize}} \quad \sum_{p=1}^P \sum_{k=1}^N \sum_{\substack{l=1 \\ l \neq k}}^N \min_{e \in r^{l,k}(R_p)} F(C_e) \\ & \text{subject to} \quad r^{l,k}(R_p) \neq \{\emptyset\}, \forall k, l = 1, \dots, N, l \neq k \text{ and} \\ & \quad p = 1, \dots, P. \\ & \quad \rho(R_p, R_q) = 0, \forall p, q = 1, \dots, P \text{ and } p \neq q. \\ & \quad FLP(e) = 0, \forall e \in \mathcal{R}. \\ & \quad P = \bar{P}. \end{aligned} \quad (4.6)$$

where  $r^{l,k}(R_p)$  is used to denote the path between the pair of nodes  $(l, k)$  in the subgraph  $R_p$ ,  $F(x)$  represents some well defined monotonically increasing function of  $x$  and  $\bar{P}$  is the desirable number of routing planes. The objective function aims to select the plane-set that contains the

paths which utilize the highest capacity between every *Ingress* – *Egress* pair. Furthermore, in accordance with Problem 1, the imposed constraints must ensure the following: first, each  $R_p$  (representing an instance of OSPF) is a connected subgraph of  $G$  ( $G$  is assumed to be connected); second, it is guaranteed that any pair of planes are disjoint with respect to the edges; third, no link is used in all the planes (which is automatically satisfied if the second constraint is); and finally, no more than  $\bar{P}$  routing planes are obtained subject to the disjoint criterion.

As also illustrated in section 4.3.1, realistically, there could exist several circumstances where this problem is infeasible, and we would need to relax constraints (b) and (c) accordingly, that were described in Problem 1. This relaxation requires us to consider minimizing the overlap between the chosen planes in a set in addition to capacity provisioning. Overlap, in this case, refers to the potential reuse of links in paths belonging to different planes. Hence, a link could appear across multiple planes and carry traffic between multiple ingress-egress pairs. To this end, relevant constraints have been integrated into the objective to reflect the projected overlaps of the paths onto each link and render the new problem as follows:

$$\begin{aligned}
& \underset{\mathcal{R}=\{R_p\}_{p=1}^P}{\text{maximize}} && \alpha \sum_{p=1}^P \sum_{k=1}^N \sum_{\substack{l=1 \\ l \neq k}}^N \min_{e \in r^{l,k}(R_p)} F(C_e) + \beta \sum_{p=1}^P \sum_{\substack{q=1 \\ q \neq p}}^P \rho(R_p, R_q) \\
& \text{subject to} && r^{l,k}(R_p) \neq \{\emptyset\}, \forall k, l = 1, \dots, N, l \neq k \\
& && \text{and } p = 1, \dots, P. \\
& && P = \bar{P}.
\end{aligned} \tag{4.7}$$

where  $\alpha \in (0, 1)$  and  $\beta = 1 - \alpha$  are arbitrary tuning parameters, chosen *a priori* and can be interpreted as a way of assigning more importance to the terms in the objectives. For example,  $\alpha \gg \beta$  indicates that more importance is to be assigned to finding planes with high capacity which would not necessarily be diverse.

### 4.3.5 Minimum-set Cover plane construction problem

In this section, the problem of building multiple planes (i.e. path-sets) is associated with the minimum-set cover problem. This is achieved herein by showing that the minimum-set cover, which is a NP-complete problem, is reducible, in polynomial time, to our problem of plane composition (i.e. building multiple planes). Therefore, it will be concluded that the plane composition problem is NP-complete. We start by summarizing the minimum set cover (MSC) and its counterpart the minimum  $k$ -set cover ( $k$ -MSC) problem. [109] below:

**Definition 4 (Minimum Set Cover Problem).** *Given a finite collection  $\mathcal{S} = \{S_i\}_{i=1}^I$  of subsets of a universe  $U$ , a set cover  $\mathcal{C} \subseteq \mathcal{S}$  is a subcollection of the subsets whose union is  $U$ , i.e.  $\bigcup_{S_i \in \mathcal{C}} S_i = U$ . Moreover, each  $S_i \in \mathcal{C}$  has an associated non-negative cost  $c_{S_i}$ . The minimum set cover problem is to compute such a subcollection  $\mathcal{N} \subseteq \mathcal{C}$  such that it is a set cover for  $U$  and its associated cost  $\sum_{S_i \in \mathcal{N}} c_{S_i}$  is simultaneously minimized. Moreover, assuming that instances of the weighted set cover are such that each  $S_i \in \mathcal{S}$  has at most  $k$  elements then the problem extends to the  $k$ -set cover problem.*

Note that the unweighted set cover and unweighted  $k$ -set cover problems are special cases of the weighted set cover and weighted  $k$ -set cover problems, respectively. Furthermore, it is known that the MSC problem is NP-complete. To show that our problem is NP-complete it suffices to show that it is in NP and that the weighted MSC problem is reducible to our problem in polynomial time.

Let the network topology being considered be defined by its connectivity graph  $G = (\mathcal{V}, \mathcal{E})$  and its associated link weight function  $w : \mathcal{E} \mapsto \mathbb{R}_+$ , that assigns a non-negative weight  $w(e)$  to each edge  $e \in \mathcal{E}$ . It is understood that  $\mathcal{V}$  and  $\mathcal{E}$  are the set of all vertices/nodes and edges/links respectively of the underlying network. Define  $\mathcal{S}$  to be a collection of distinct subsets of  $\mathcal{E}$ , that is to say:  $\mathcal{S} = \{S_i\}_{i=1}^I$  where  $S_i \subset \mathcal{E}$  for each  $i = 1, 2, \dots, I$  so that for any  $i \neq j$ ,  $S_i \neq S_j$ . Such a collection of subsets can be obtained, for example by constructing all spanning trees of the underlying graph  $G$ , see for example [110]. Each tree  $S_i$  is simply a subset with at most  $|\mathcal{V}| - 1$  elements (i.e. edges ‘ $e$ ’) chosen from  $\mathcal{E}$ ; with an associated cost  $c_{S_i} = \sum_{e \in S_i} w(e)$ . It is

easy to conclude that  $\bigcup_{i \in \mathcal{I}} S_i = \mathcal{E}$ . Now given  $\mathcal{S}$ , each member element  $S_i$  has a path connecting all possible Ingress-Egress pairs hence representing a valid routing plane. We aim to find the subcollection  $\mathcal{N}$  of RPs of minimal dynamic cost (section 4.5.1) that utilizes every link in the network. In other words, we desire an  $\mathcal{N}$  such that  $\bigcup_{S_i \in \mathcal{N}} S_i = \mathcal{E}$  and  $\sum_{S_i \in \mathcal{N}} c_{S_i}$  is minimized. This is clearly the minimum set cover problem, by definition. It is now clear that our MPR problem is a generalization of this MSC problem, therefore it is in NP and also NP-complete.

Problem 1 and its relaxation as formulated in equation 4.7, is NP-complete as shown in this section <sup>§</sup>, thus we will need to resort to heuristic algorithms for computing useful solutions in Section 4.4 followed by Section 4.5. In particular, for some network  $G$ , the approach we will adopt is to: first of all, construct a highly redundant collection of subgraphs (subsets) of the network and from these subgraphs, select a set of connected subgraphs within this collection of connected subgraphs (i.e. a set  $R$ ). To this end, several approaches will be presented in Section 4.4; followed by routing plane construction mechanism in Section 4.5.

## 4.4 Algorithms for Constructing the comprehensive finite Set (Candidate Routing Planes)

In this section, we propose algorithms for constructing multiple valid candidate routing planes ( $\{S_i\}_{i=1}^I$ ) and in so doing construct a valid collection  $\mathcal{S}$ . We note that this collection would represent a cover for the set  $\mathcal{E}$ . Every subset  $S_i$  of edges must contain a link between all Ingress-Egress pairs in  $G$ , in other words, each subgraph  $G_i \stackrel{\text{def}}{=} (\mathcal{V}, S_i)$  of  $G$  must connect all Ingress-Egress pairs <sup>¶</sup>. To this end, we adopt the following approach: 1. Initially, given the underlying network topology  $G$ , we construct a set  $\mathcal{S}$  whose elements  $\{S_i\}_{i=1}^I$  are subsets of the set of all edges  $\mathcal{E}$  of the underlying network. We impose a further constraint that each set  $S_i$

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<sup>§</sup>We re-associate the NP-Complete Minimum Set Cover Problem to our solution for constructing problem of building multiple planes in random graphs as also adopted in case of MPR [17]

<sup>¶</sup>Although RPs are practically instances of OSPF, we don't adopt the method applied in previous work and MT-OSPF as we apply comparisons of paths from the start rather than implicitly being formed as a consequence of weight distribution in networks. Once selected and built, planes are reversely converted into MT-OSPF via reverse Dijkstra

must render a connected network (i.e. with routes linking all Ingress-Egress pairs that include some of the transit nodes/routers). Consequently, each  $S_i$  would represent a candidate plane.

2. Subsequent to obtaining the candidate planes, each candidate plane would be associated with a dynamic cost  $c_{S_i} = \sum_{e \in S_i} w(e)$ . Consequently, we aim to derive the minimum set cover  $\mathcal{N}$  based on the cost by applying any state-of-the-art algorithm such as [109].

#### 4.4.1 Constructing multiple candidate planes I: Edge deletion

This approach aims to construct several subgraphs of  $G = (\mathcal{V}, \mathcal{E})$  that would represent a candidate routing plane each of which would be associated with a dynamic cost. The algorithm is based on computing the shortest (least cost) paths from a fixed node to the rest of the nodes in the network, removing the most used edge and then repeating the process for the remaining nodes until all edges have been deleted (in order to reduce the number of times a link is reused). From these paths a subgraph connecting all Ingress-Egress pairs is formed by selecting paths with the overall least cost. The composed subgraphs would correspond to the candidate planes  $S_i$ . The proposed procedure is outlined as follows:

##### Forming the subgraphs

1. Given the full network topology  $G$  with  $\mathcal{V} = \{v_i\}_{i=1}^N$  and  $\mathcal{E} = \{e_j\}_{j=1}^E$ .
2. Set  $G' = G$ .
3. For  $l' = 0$  until  $l' = E - 1$ :
  - (a) Set  $i = (l' \bmod N) + 1$  and  $l = l' + 1$ .
  - (b) Consider the graph  $G'$  and the  $i$ -th node, say  $v_i$ . Find the shortest path (based on the number of hops) using Dijkstra's algorithm, for instance, between  $v_i$  and every other node in the network to obtain the paths  $\hat{S}_l = \{r_{i,j}(l)\}_{j=1, j \neq i}^N$ .

(c) Count the number of times the edge  $e_j \in \mathcal{E}$  appears in each of the paths  $r^{i,j}(l)$ ; where  $r^{i,j}(l)$  is the path between node  $i$  and  $j$  at the  $l$  iteration.

(d) Delete the edge  $e_j$  that appears the most from  $G'$ .

### Forming the connected subgraphs

4. Choose the set  $\hat{S}_l$  that has the highest cardinality, let this set be of cardinality  $L'$ .

5. For  $l' = 1$  until  $N - 1$  (i.e. excluding one node):

(a) Form the new set of paths  $S_{l'} = r^{1,j}(l')$ .

(b) Consider each isolated node and add a path to  $S_{l'}$  in order to make it reachable from  $v_1$  by choosing paths from the other collections, i.e. from  $\hat{S}_2, \hat{S}_3, \dots, \hat{S}_{E-1}$ . Start with the path of least cost (i.e. choose the path with  $\min_{e \in r^{i,j}} \frac{1}{C_e}$ , of least resistance).

(c) Delete this chosen path, repeat for all isolated nodes and stop once  $S_{l'}$  is a  $\parallel$  subgraph of  $G$  (i.e. candidate RP connecting all Ingress-Egress pairs).

6. Return the  $E - 1$  derived subgraphs, i.e.  $\{S_i\}_{i=1}^{E-1}$ .

Among the collection of the candidate planes  $\{S_i\}_{i=1}^{E-1}$ , each of which being associated with a cost  $c(S_i)$  \*\*, a collection  $\mathcal{R}$  is to be constructed that would represent the desirable RPs of minimum cost that simultaneously form a cover for the network  $G$ .

## 4.4.2 Constructing Multiple Candidate Planes II: All Trees

In this section, we propose an approach for building the distinct trees of  $G$  that correspond to the candidate RPs. To this end, we introduce a result in graph theory that recovers all trees of  $G$ .

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<sup>||</sup>This can be done using breadth first search for example.

<sup>\*\*</sup>This dynamic cost will be determined based on our proposed cost function.

**Definition 5** (Tree). A subgraph  $G_i \stackrel{\text{def}}{=} (\mathcal{V}, S_i)$  of  $G \stackrel{\text{def}}{=} (\mathcal{V}, \mathcal{E})$  is called a **tree** if it is a tree graph structure<sup>††</sup> containing all the vertices in  $\mathcal{V}$  that connect all the Ingress-Egress pairs.

For some given  $G$ , the problem of enumerating all its trees has a long history (see for example [110, 111] and references therein). We adopt the method proposed in [111] which enumerates trees by swapping edges in a fundamental cycle; in fact, their method can find and list all trees for the unweighted and undirected graph in  $O(N_T + V + E)$  where the  $N_T, V$ , and  $E$  are used to denote the number of trees, vertices and edges, respectively, in  $G$ . Their basic algorithm is summarized in Algorithm 3, and an optimized version of their algorithm is presented in their paper.

We now define some subroutines used in Algorithm 3:

1. **PrepareForSon( $e_i$ )**: If  $i = 1$  then this subroutine contracts nontree edge  $f$  in  $AG$  ( $AG$  is a data structure that maintains the current graph). Next it combines all cycles in  $C$  which contain tree edge  $e_i$  with cycle in  $C$  corresponding to the edge  $f$ .
2. **PrepareForSonsSiblingBranch( $e_i$ )**: This routine contracts  $e_i$  in all cycles in  $C$  containing  $e_i$  and modifies  $AG$  in order to reflect this contraction.
3. **PrepareForFinalSon**: This subroutine deletes the nontree edge  $f$  from  $AG$  and modifies  $C$  to reflect this deletion.

In fact, we can count the number of spanning trees *a priori* given the underlying network topology using Kirchoff's Matrix-Tree Theorem (see texts [112, 113] for details) stated below. It is notable that considering the variable combination of Ingress and Egresses across the random topologies we consider in existence of a transit space (with the possibility of every node being an Ingress or an Egress), the spanning tree problem can be reduced to our special case of finding the trees that ensure the connectivity between every Ingress-Egress pair corresponding to a plane (not necessarily including the transit nodes).

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<sup>††</sup>Unlike a spanning tree that would contain all vertices in a graph (tree assumes the existence of a transit space)



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**Algorithm 3** Find all Trees of  $G$ 

---

**Require:**  $G$ .

```
1: procedure ALLTREES( $G$ ) ▷ Find all trees of  $G$ 
2:   Find a tree  $T$  of  $G$ ;
3:   Initialize data structures (i.e. let  $F = G \setminus T$ );
4:    $mf \leftarrow$  a multiedge in  $F$ ;
5:    $f \leftarrow$  an edge in  $mf$ ;
6:    $F \leftarrow F \setminus mf$ ;
7:    $c_{fun} \leftarrow$  the fundamental cycle of  $f$  w.r.t  $T$  in  $G$ ; ▷ In order of occurrence
8:   for  $i = 1 : k$  do
9:      $T' \leftarrow (T \cup f) \setminus e_i$ ;
10:    CHANGES  $\leftarrow$  CHANGES +  $\{(e_i, f)\}$ ;
11:    Output: CHANGES; ▷ Difference from last generated tree
12:    CHANGES  $\leftarrow \emptyset$ ;
13:    PrepareForSon( $e_i$ );
14:    if  $F \neq \emptyset$  then
15:      Go to 4;
16:    end if
17:    CHANGES  $\leftarrow$  CHANGES +  $\{(e_i, f)\}$ ;
18:    if  $i < k$  then
19:      PrepareForSonsSiblingBranch( $e_i$ );
20:    end if
21:  end for
22:  Restore all changes made to graph and data structures in for-loop;
23:  Restore multiedge  $mf \setminus f$  to  $F$ ;
24:  PrepareForFinalSon();
25:  if  $F \neq \emptyset$  then
26:     $T \leftarrow T'$ ;
27:    Go to 4;
28:  end if
29:  Restore changes made by PrepareForFinalSon to the graph and data structures;
30:  Restore edge  $f$  to multiedge  $mf$  in  $F$ ;
31: end procedure
```

---

**Definition 6** (Graph Laplacian). *The **graph Laplacian**  $L$  of a graph  $G \stackrel{\text{def}}{=} (\mathcal{V}, \mathcal{E})$  with  $n$  vertices  $\mathcal{V} = \{v_1, v_2, \dots, v_n\}$  is an  $n \times n$  matrix with entries:*

$$L_{ij} = \begin{cases} \deg(v_j) & \text{for } i = j, \\ -1 & \text{for } i \neq j, \\ 0 & \text{otherwise.} \end{cases}$$

*Equivalently, if  $D$  is a diagonal matrix with  $D_{jj} = \deg(v_j)$  and  $A$  is the graph adjacency matrix, then  $L = D - A$ .*

**Theorem 1** (Kirchoff's Matrix-Tree Theorem). *Let  $G \stackrel{\text{def}}{=} (\mathcal{V}, \mathcal{E})$  be an undirected graph and  $L$  its associated graph Laplacian, then the number of spanning trees contained in  $G$  can be computed as follows:*

1. *Select any vertex  $v_j$  and eliminate the  $j$ -th row and column from  $L$  to obtain a new matrix  $\bar{L}_j$ ;*
2. *Then the number of spanning trees in  $G$  is*

$$N_T = \det(\bar{L}_j). \quad (4.8)$$

The trees constructed using Algorithm 3 now form the elements of the collection  $\mathcal{S}$ . Given  $\mathcal{S}$ , we propose the use of a greedy algorithm to solve the NP-complete minimum set cover problem in the following section.

## 4.5 Finding multiple minimum cost RPs: The minimum set cover

Having constructed the candidate routing planes  $\mathcal{S}$  (i.e. The set) using the approaches outlined in Section 4.4, we aim to obtain the minimum set cover. To this end, several planes from  $\mathcal{S} =$

$\{S_i\}_i$  should be selected such that their union coincides with the underlying network topology, rendering a minimum cost set cover solution (*wrt* based on a certain cost function associated with each  $S_i$ ). As discussed earlier, this can be recast as the MSC problem. Several approaches have been proposed in recent years on how to solve the MSC problem, a useful survey of current approximate algorithms can be found in [114].

A well known and straightforward greedy algorithm for solving this problem exists [109, 115]. Starting with an empty collection of subsets in the solution and no covered item, the following procedure is iterated. Define  $N_{S_i}$  to be the number of uncovered items in  $S_i$  and define the *current* ratio  $r_{S_i} = \frac{f(S_i)}{N_{S_i}}$ , let  $S^*$  be a set with minimal  $r_{S^*}$ . The algorithm then adds  $S^*$  to the collection of subsets of the solution and defines the items in  $S^*$  as covered and assigns a cost  $r_{S^*}$  to all items that are now covered which were uncovered before this iteration. In fact a modification that improves on the complexity of this algorithm, called the greedy algorithm with withdrawals, was proposed by Hassin and Levin in [109]. We apply this modified approach in order to construct the minimum set cover from  $\mathcal{S}$ .

Furthermore, to solve our problem, we propose a modification of the simple greedy algorithm, studied in [115], wherein the cost  $f(S_i)$  associated with the unused subsets  $S_i$  changes with each greedy iteration. This new modification aims to dynamically capture the requirement that the selected topologies are relatively as diverse as possible (with respect to the links used). Therefore we use our similarity metric (4.1) to adjust the cost associated with selecting a plane at each greedy iteration  $t \in \mathbb{N}_0$ . We denote this new dynamic cost function by  $f_t(S_i)$ , where the index  $t$  has been included to emphasize the fact that the cost changes with  $t$ .

In what follows we provide an explicit mathematical expression for our dynamic cost function and consequently outline the steps of the proposed algorithm in Sections 4.5.1 and 4.5.2 respectively.

### 4.5.1 The cost function

The associated cost function with which to perform the minimum set cover is explicitly defined as:

$$f_t(S_i) = \begin{cases} \alpha \sum_{k=1}^N \sum_{\substack{l=1 \\ l \neq k}}^N \max_{e \in r^{l,k}(S_i)} F(C_e), & \text{for } t = 0 \\ \alpha \sum_{k=1}^N \sum_{\substack{l=1 \\ l \neq k}}^N \max_{e \in r^{l,k}(S_i)} F(C_e) + \frac{\beta}{|\tilde{\mathcal{R}}_t|} \sum_{S_j \in \tilde{\mathcal{R}}_t} \rho(S_i, S_j), & \\ \text{for } t > 0. \end{cases} \quad (4.9)$$

where  $F(x) = \frac{1}{x}$  and  $\tilde{\mathcal{R}}_t$  is a set of those planes that have already been selected as routing planes. Note that at the start of the MSC algorithm the set  $\tilde{\mathcal{R}}_t$  will be empty, i.e.  $\tilde{\mathcal{R}}_t = \emptyset$  with cardinality zero, hence we choose the best routing plane in terms of capacity in the first iteration.

The first term of the cost function  $f_t$  will be large when  $C_e$  is small and therefore penalizes planes containing paths with very low capacity. Consequently, this sum ensures that planes having the best capacity between all Ingress-Egress pairs are preferred. In addition, the second term in the cost function introduces a measure of the correlation between the current plane  $S_i$  and every other routing plane already chosen during the implementation of the MSC algorithm. Therefore this sum will be small when  $S_i$  is most different from the already chosen planes.

### 4.5.2 The MSC-based RP construction algorithm

The following iterative procedure finds the near-optimal cover for the edge set of  $G$ .

(S.1) Set  $\tilde{\mathcal{R}}_t = \emptyset$  and  $t = 0$ .

(S.2) If  $G = \bigcup_{R_p \in \tilde{\mathcal{R}}_t} G$  then stop and return  $\mathcal{R} = \tilde{\mathcal{R}}_t$ , since  $\tilde{\mathcal{R}}_t$  is a cover. Otherwise, compute the ratio:

$$r_{S_i} = \frac{|S_i|}{f_t(S_i)}, \quad (4.10)$$

and select the plane  $S_j$  that maximizes this ratio.

(S.3) Add  $S_j$  to  $\tilde{\mathcal{R}}_t$  as follows: set  $R_{t+1} = S_j$  and then replace  $\tilde{\mathcal{R}}_{t+1}$  with  $\tilde{\mathcal{R}}_t \cup R_{t+1}$ .

(S.4) Set  $S_j = \emptyset$  and return to step (S.2).

## 4.6 Performance Evaluation

We evaluate our proposed framework using extensive random simulations. The algorithm used to generate the graph can best be described as a random walk. Every one of  $V$  nodes is added one by one and is connected to a previous node, within its constraints. This algorithm results in a random connected graph that includes all the nodes. Missing edges are then randomly added until the desired random sparseness is achieved. Randomly generated sets of topologies with different randomly applied meshings/sparseness (i.e. average node degree) levels, varying possible number of gateways and destinations (i.e. ARs) are presented in Table 4.2 (the remaining nodes are transit (i.e. not source nor sink)). The capacity between any two nodes is randomly generated based on its distance from a gateway, with higher capacity corresponding to lower distance from the gateway (reflecting heterogeneity and practical deployments).

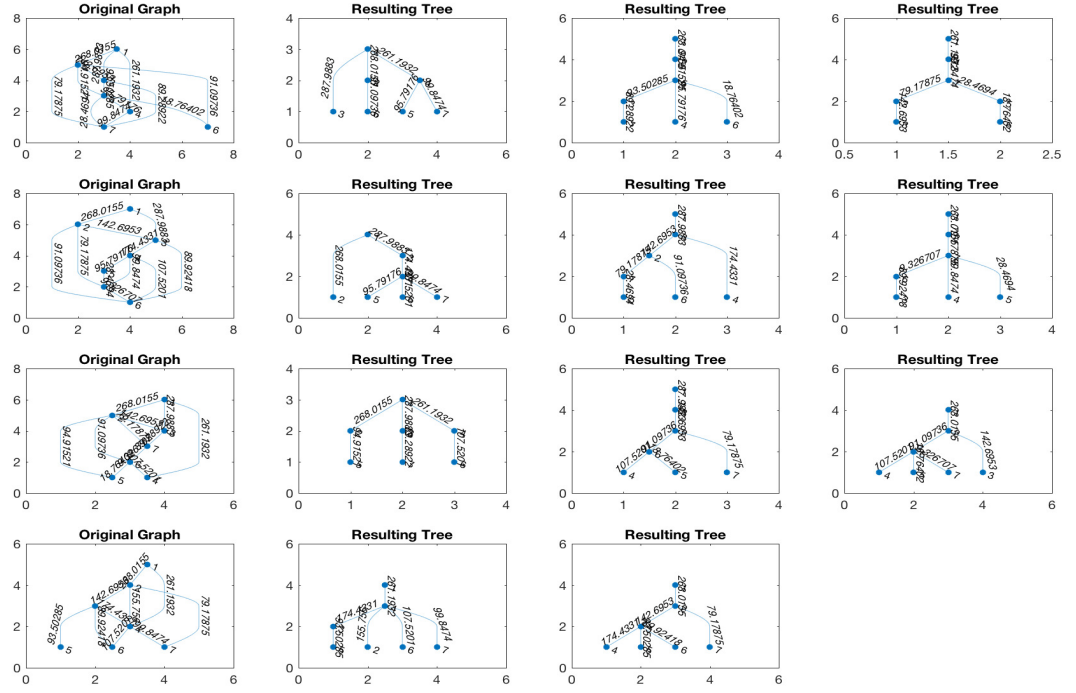
In general, the process of finding all trees as an input set into a function is extremely computationally expensive. For complete graphs, the number of such trees is on the order of  $O(v^{v-2})$ . As such, it is useful to be able to approximate a solution by an iterative approach. To this end, a greedy heuristic is developed for each step of MSC RPs' heuristic approach to find a near optimal tree at each iteration (based on our cost function) that concatenate to represent the near optimal MSC RP set solution (as generally set out in equation (8) with our dynamic cost function). Given an input graph, our heuristic approach applies the hill climbing algorithm in order to obtain a set of near-optimal RPs. Initially, the minimum tree on the input graph is obtained (first RP) followed by changing every edge (i.e. hill climbing) on the concerning tree in the attempt to find the near-optimum diverse RP set. Therefore, after obtaining the initial RP that we use as reference, in case a more suitable candidate RP (tree) is obtained in our heuristic search, the concerning candidate would replace its predecessor in each iteration. The

Topology	Nodes	ARs	Avg. Node degree	Gateways	RPs
T1S1	7	3	2.35	1	2
T1S2	7	3	3.71	1	3
T1S3	7	3	4.26	1	3
T1S4	7	3	4.65	1	3
T2S1	18	6	3.23	2	4
T2S2	18	6	3.67	2	5
T2S3	18	6	4.16	2	7
T2S4	18	6	4.91	2	8
T3S1	33	14	3.18	3	8
T3S2	33	14	3.62	3	9
T3S3	33	14	4.45	3	11
T3S4	33	14	4.88	3	15
T4S1	60	25	3.45	5	13
T4S2	60	25	3.87	5	17
T4S3	60	25	4.69	5	22
T4S4	60	25	5.87	5	27

**Table 4.2:** Setup of the Randomly generated topologies

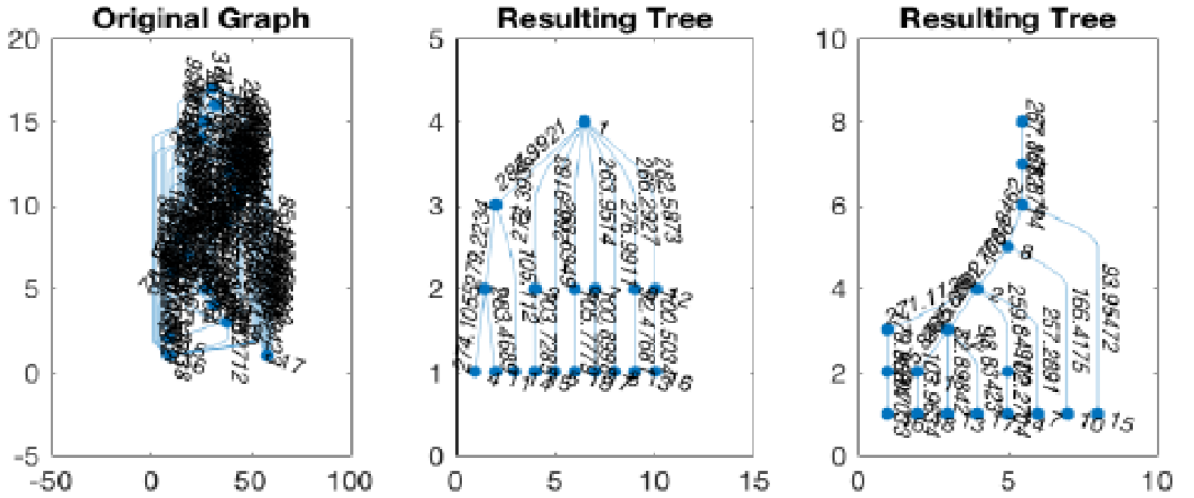
algorithm will stop once the best near optimum minimum set cover relative to our objective function's criteria (namely capacity and correlation) is obtained. The number of diverse MSC RPs obtained for the different randomly generated graphs with random sparseness levels using the aforementioned approach is presented in Table 4.2. It is important to note that legacy MPR's offline algorithm failed to generate any diverse set of RPs in our studied random scenarios. The applicability of our approach in constructing a paths diverse set of RPs for such wide ranging varying random scenarios is indicative of the comprehensiveness of our solution. We note that density in topologies could be very high and the network becomes highly meshed and complex. The results for networks of such scale are indicative of the great scalability of our approach. To this end, the effectiveness of our paths diverse approach for large-scale random topologies is demonstrated which distinguishes our approach from the legacy MPR's RP construction method.

Figure 4.2 illustrates the  $T1S_y$  topologies along with the resulting trees for four different random levels of sparseness (as presented in Table 4.2). The links' capacities are randomly assigned based on their distance from the gateway (higher if closer - reflecting on heterogeneity



**Figure 4.2:** Random network topologies (T1Sy) with the resulting Trees (i.e. RPs)

[20]). We have chosen not to illustrate the other topologies due to the high link and node density as exemplified in Figure 4.3.



**Figure 4.3:** 18 Node Randomly Generated graph (i.e. T2S3) with two exemplary Resulting Trees (i.e. RPs)

MSCs main working assumption is based on similar structural assumption as MPR, but presents a step further in tackling the issues that will emerge as the novel networks and their topological configurations roll out in the future, as discussed in Chapters 2 and 3. It can be considered that these networks will present a significantly novel operational space from the ones typically considered in the current routing solutions, due to the extent of the topological configurations and sizes. From this position, it can be discussed that MSC is an IP-based scheme that is cheaper than MPLS in terms of protocol overhead, already proven (via MPR principle) to outperform MPLS over series of major performance criteria, and it uses the whole topology, from the start of the process (i.e. offline algorithm), in a very practical manner.

In terms of IP-based TE schemes, MSC does belong to that category since it uses default IP-routing tools (MT-OSPF being a standardised protocol [64]). However, MSC is very different to many existing IP-based schemes as it is not about convergences of shortest path routes or intelligent planning of equal cost paths via clever weight adjustments (i.e. ECMP) that are the most important themes and objectives of many existing IP-based TE schemes. It is therefore essentially different, and uses the whole topology as the input for its offline algorithm and utilises the whole of it for planning the routing in the online mode. It is highly practical and entirely topology-aware. MPR work already proves that the approach offers many gains over the rival schemes. So, what makes MSC topology-aware and comparably different as an approach to other schemes, IP-based and MPLS as well? This is actually a very important point in evaluation of MSC since it is based on extending the types of topologies of IP access networks, and, conducting the experiments and analysis with these, random topologies, as the solutions space:

- MPLS TE commonly focuses on pairs of Ingresses-Egresses in the network, i.e. uses an algorithm to build paths between them. Then for all Ingress-Egress pairs, some objective could be pursued that can be implicitly assumed to be convenient as a holistic objective for the whole network. In this way it can be argued that the TE is a topology-aware solution. However, for the most common TE adaptation of MPLS that we use to compare



with MPR/MSR, K path MPLS, K paths are built between Ingress-Egress pairs, where one of these paths is disjoint. So topology-awareness, use of all links, balancing between different Ingress-Egress pairs is not explicitly handled.

- IP-based TE schemes do have a degree of explicit topology-awareness as a performance improvement property. This is because they are adjusting, at least a significant portion of them, weights throughout to whole network. Then paths are built as the algorithmic product of the weights summation. This can be a slow process of path convergences. In ECMP it is additionally expected that the link weight summation will produce multiple paths that have equal costs. In this case, topology awareness is not directly applied but it is assumed that it will be indirectly integrated by involving all paths. The shortest paths rendered by OSPF/Dijkstra for example, are naturally being produced as a summation of the algorithm that uses all the links in the networks, i.e. the whole topology is implicitly considered.
- MPR applies a more direct topology-aware solution. In building planes, it has specific rules that when all planes are composed in a set, every link has to be used at least once. Also, some links should be alleviated from carrying all traffic, thus, a condition was applied that a link should not be used all the times. This is the planning phase of the algorithm, prior to traffic insertion in the network, i.e. offline algorithm. So it can be said, MPR applies topology-awareness from the start of the process since planes would be distributed over the whole network without omission of links and with care that some links are not overused. However, it can be argued that MPR is semi-explicit in applying the total awareness of topology. It uses weights to build planes, thus, does not have explicit control over paths as paths are built after algorithmic summation of weights, hence, actually paths as a consecutive string of links can be diverse and uncontrollable depending on the topological setup of links, value of weights etc. Rather, MPR planes and their paths distributions are products of rendering the summations of link weights in the network, thus, control of paths is rather implicit.

Based on the above analysis, MSC can be further confirmed as a TE scheme that applies explicit awareness of topology. Firstly, through its offline algorithm, then holistically as a TE scheme that applies its online algorithm that is presented in the next Chapter. In the offline algorithm, paths are built using a method that applies graph-based path segments adapted from the graph theory models, hence they enable inclusion of all links that form each path and can accordingly be controlled during the construction process. Such a feature and the extent of its applications in large, random topological configurations are unique as they allows for control of how packets are to be distributed in the network in the offline mode and prior to the actual insertion of traffic. Results for MPR and its offline algorithm, which similarly prepares for packet insertions but in less random topologies, show that a balanced distribution of paths over the routing resources of the entire networks topology is enough to offer performance gains in the online mode. In addition to this property of the offline algorithm that is also present in the case of the MSCs offline algorithm, the specific and novel features of the offline algorithm based on graph-based modelling are in:

- 1) Overseeing and planning path overlaps when choosing routing plane sets, i.e. between multiple paths of all Ingress-Egress pairs in the network. The defining feature for this property of the algorithm is inclusion of the Graph Correlation Metric from subsection 4.3.2, equations (4.1) and (4.2), in the minimum set cover cost function of equation (4.9) for measuring the cost of a new plane that is added to the existing plane(s) in a set. Hence, the final rendering of the planes in a plane set includes the cost measure of their path overlaps.

- 2) Deterministic planning of the use of the link capacities in paths across the routing planes. A planned use of the capacity of a path is in the theoretical maximum data rate that can be transmitted over it. This parameter is dependent on the paths bottleneck, which can be: a link with minimum capacity in the path; and/or, minimum available residual capacity in one of the links in the path, which is subject to dynamic use of each link by other paths. This is achieved by inclusion of the inversely proportional function of a link capacity or its residual capacity if it is already used by path(s) in the previously selected plane(s), as shown in equation (4.9)

This means that MSC in its offline mode exerts a very high awareness of topology and a very high control of how it is used in building paths. Thus, the applied scheme opens up random topological scenarios, something that has been omitted in the literature up to now and is becoming increasingly important in the network design. The term random topology has been used to include the network configurations that are defined as random graphs in the standard graph theory based definition. As analysed in the next section, such an offline algorithm and the facilitated distribution of paths already suffices to prepare the network performance for balanced and optimally distributed use of its routing resources.

Conveniently the approach of applying a cost function to render plane compositions offers a stopping point in constructions of planes sets. The function indicates minimal gains when new planes are added after a certain number of planes have been included in a set. This property is already detected in the initial testing of the idea of multi-plane routing using MRP [16] and general investigation of multipath routing technique for per-packet diversities [116]. Hence, there is a limit to how much benefits are achieved in network performance criteria when paths continue to be added as routing choices. This somehow supports the design decision to limit the number of planes via their algorithmic construction using the two algorithms presented as choices (i.e. Edge deletion and All Trees) due to the computational complexities in larger topologies/graphs and resorting to a heuristic solution using the hill climbing machine learning algorithm.

## **4.7 Summary**

In this chapter, IP TE-based MPR has been extensively redesigned and reformulated to suit the future random wireless all-IP access network structures. The variable and disparate nature of access network structures as reflected in the evolutionary access networks, along with the rise of IP-based real-time applications demand a new consistent routing optimization paradigm. To this end, a comprehensive TE mechanism applicable to random access networks is proposed.

This mechanism allows the network to maintain a set of diverse independent logical topologies which can be used to balance the traffic load in the network. Our approach adopts a dynamic minimum set-cover based cost function in order to construct a diverse set of RPs while also considering capacity. The results demonstrate the effectiveness of our approach by creating a diverse set of RPs for a wide-ranging set of randomly generated graphs of different sparseness levels where the legacy MPR's TE mechanism is redundant.

In the upcoming chapter, the offline composition of multiple planes in random networks will be expanded with the introduction of the online Traffic flow. To this end, a Comprehensive Multi-Topology Minimum Set Cover Link-State Routing Approach for Emerging Random All-IP Access Network Topologies will be proposed and investigated. An online TE method will be adopted to optimize the network's performance. Performance evaluation in terms of various measures will be presented that include comparisons against some rival routing schemes namely legacy OSPF.

# 5

## **A Comprehensive Multi-Topology Minimum Set Cover Link-State Routing Approach for Emerging Random All-IP Access Network Topologies**

### **5.1 Introduction**

In the previous chapter, a novel MSC-based offline RP construction approach was proposed in consideration of variable and disparate nature of access network structures. The obtained results demonstrated the effectiveness of our approach by creating a diverse set of RPs for a wide-ranging set of randomly generated graphs of different sparseness/meshing. In this chapter, we extend the proposed methods in the previous chapter by adding the online TE element to our study drawing extensive comparisons against rival strategies in terms of various performance metrics. To this end, a comprehensive MT-OSPF based link-state TE approach is proposed for the emerging random all-IP access network topologies.

The unpredictable nature of future access network structures necessitates consistent adap-

tations by network providers to enable disruption and loss free networks supported with the ubiquitous IP infrastructure. Correspondingly, a routing optimization mechanism applicable to randomly shaped all-IP access networks must be developed. In this chapter, a comprehensive multi-topology minimum set cover approach is proposed in consideration of the randomness of future access networks. This approach consists of an offline (as presented in Chapter 4) and an online Traffic Engineering (TE) method. To this end, we proposed a novel MSC-based paths-diverse offline TE algorithm which is comprehensively applicable to randomly shaped access network structures in the previous chapter. Our simulation results demonstrate the applicability of our approach to complex random networks of different sizes and sparseness (i.e. meshing). Hence, the comprehensive applicability of our novel approach is verified. Finally, it is shown that for ranges of random topologies, our paths-diverse MSC-based approach improves networks performance as compared with rival strategies in terms of various online performance metrics.

The heterogeneity of emerging access networks' structures (as also presented in) is also a significant factor in conjunction with the considerations of randomness in the network topology. Heterogeneity is also integrated in our investigation of the different TE strategies studied in this chapter. To this end, our proposed MSC-based approach and its QoS enabled counterpart (QMSC) are compared against OSPF, InvCap and MPLS TE approaches.

## **5.2 Elaboration of Novelty**

### **5.2.1 Concept**

Our MSC-based problem aims to achieve similar TE objectives as MPR consisting of a paths-diverse offline TE method combined with an online TE mechanism with a fundamentally different algorithmic approach. This is derived by our MSC-based approach aiming to be much more widely applicable and address the unpredictable future access networks' complex random structures (i.e. random graphs) where the MPR is deficient. To this end and in order

to facilitate a comprehensive TE approach, an extensive novel offline RP construction method is designed and adopted for our proposed MSC based problem as it will be laid out. To be more specific, MPR is based on a link weight penalization-based cost heuristic whereas MSC explicitly compares paths by adapting a novel dynamic cost function with correlation and link capacity elements followed by reverse engineered Dijkstra link weight assignment for every path-set corresponding to every RP (hence MPR compares paths implicitly, whereas MSC does it explicitly using graph based representations in the offline algorithm). Figure 2.6 illustrates how three sets of shortest paths can be combined to form three RPs so as to maximize path diversity between a single ingress/egress pair (from node S to node D). \*

Correspondingly, our MSC-based approach divides the physical topology into multiple logical planes called RPs. Each RP represents an instance of OSPF associated with a dedicated Dijkstra-based link weight configuration. The RP construction problem relaxation will allow for RPs to overlap with another or share any subset of the underlying network routing resources rather than being strictly edge-disjoint. Our approach enables path diversity through an offline MSC-based algorithm which leads to the full utilization of resources (i.e. links) in the network. Routes are defined through Routing Information Bases (RIBs) (i.e. control plane) and Forwarding Information Bases (FIBs) (i.e. data plane), each representing one RP, augmented in every router accordingly. MPR originally exploited three DiffServ [91] integrated bits in the Type of Service (ToS) field of IP(V4) packets specified by IETF in [91]. In case DiffServ is not used or in case of IPV6 (where more redundant bits are available), MPR/MSC would have access to more bits, hence, more planes could be supported by ToS field. Therefore, routers are configured to recognize the RPs through the unused bits. Consequently, MSC can exploit the structure in the IP header without imposing extra overhead onto each packet. This is opposed to MPLS where a 32-bit MPLS label stack is imposed on each IP packet by encapsulation causing overhead and router's configuration complexity.

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\*It is notable that the set of shortest paths between every ingress-egress pair should not be necessarily disjoint as a result of the relaxation that will be introduced later

### 5.2.2 Contributions

The main contribution of this chapter is the presentation of a thorough performance analysis comparing our proposed MSC-based approach and its QoS enabled counterpart (i.e. QMSC) with its rival strategies namely OSPF, InvCap and MPLS. We also introduce the possibility for the existence of more than one gateway in a given access network as reflected throughout the investigated topologies. Moreover, we integrate the increasingly expected [20] heterogeneous nature of the emerging access networks' capacities in our investigation of the different TE approaches in random topologies. It is notable that, as it will become apparent, the applicability of our approach in constructing a paths-diverse set of RPs for such wide ranging varying random scenarios is indicative of the comprehensiveness of our solution. To this end, a comprehensive multi-topology MSC link state routing scheme for emerging random all-IP access networks is proposed.

## 5.3 System Model

### 5.3.1 Experimental Setup

In case of MSC, the offline TE approach which will be presented in the following section, is applied to build RPs for the different topologies as presented in Table 4.2 ahead of the traffic flow into the network. For the MPLS case, Dijkstra-based K-path routing is applied in order to construct a similar number of RPs as the MSC case, creating  $Z$  multiple paths for every *Ingress -Egress* pair. In this case (MPLS offline TE, i.e. network planning phase), we ensure the existence of one edge-disjoint path (or atleast a maximum number of edges being disjoint if not all) with a hop-count threshold (a set of given metrics as detailed in [9]). This would result in a controlled number of LSPs (i.e. as many as desired by the network planner). This method of LSP construction targets to alleviate the common overhead and scalability issues in MPLS. The criteria are set such that the same number of LSPs equivalent to RPs in case of MSC are obtained ( $Z \equiv N$ ).



We evaluate our MSC-based approach using extensive packet level NS2-based simulations interfaced with Matlab. Sets of random topologies with different sparseness/meshings (as presented in Table 4.2) are used for this study. The performance of MSC and QMSC under different meshing scenarios is compared with MPLS, while using legacy OSPF and OSPF InvCap approaches as the baseline methods for comparisons. It is notable that the legacy OSPF method and OSPF InvCap method are differentiated based on link weights set to 1 (hop-count based) and inverse capacity-based weight setting, respectively. Sources and destinations of traffic and the duration of the corresponding flows are also randomly selected throughout the simulation time. As the simulation runs, traffic is generated with a decreasing session arrival time so as to load the network until congestion level. With a new session request at the Ingress (i.e. an AR or the gateway), it checks for bandwidth availability on the set of potential path(s) to reach the Egress, regardless of the method being used (OSPF, InvCap, MSC, MPLS or QMSC). Given the link-state nature of the aforementioned TE strategies, ARs and the GW are aware of the traffic dynamics and the links' status in the network at different time frames. Traffic rate is increased by reducing inter-arrival times of sessions at *Ingresses*. Beyond the network saturation point, the network becomes significantly congested and packet rate drops as a result. We should note that the capacity that we have associated on each edge was normalized between 16 to 32 MBs, based on the random edges created on the offline (Matlab) algorithm. In this setting, relative distance from a gateway is taken into consideration, with higher capacity corresponding to lower distance from the gateway and vice versa reflecting upon heterogeneity and future practical deployments. Hence, the experiments have the same framework of network conditions as in the case of MPR validations shown in Chapter 3 but are taken in the wild by including network topologies and sizes that correspond to random graphs/topologies constructed in the previous Chapter.

High computational complexity associated with the spanning tree algorithms adapted for plane constructions in the topologies shown in Chapter 4 (i.e. Edge Deletion and All Trees spanning tree algorithm). As a remedy, a greedy algorithm, specifically the hill climbing ma-

chine learning algorithm, is used as a complementary solution for networks with more than 7 nodes in the performance evaluations. It aims to shortcut the discovery process of finding a set of routing planes that come close to optimality based on the set out offline algorithm criteria. The hill climbing does find a close to optimum solution for all the studied topologies including the very extreme case with 60 nodes as shown in Table 4.2 in Chapter 4. These results for 60 node topologies for online algorithm have been omitted since they do not represent a major shift from the results for 33 nodes which have shown discrepancies and variations in results due to expansion of the topology size as discussed in the following subsections. Also, such extreme topologies are considered too large for a real world access topology without partitioning.

### **5.3.2 The online RP selection**

We note that the same online TE RP selection approach as in [17] is adopted (as also presented in Appendix A. As explained in the previous Chapter, the mere ability of the MSCs offline algorithm to render a plane set in extreme cases of topologies, compared to the topologies tested for MPR, is the validation of the comprehensiveness and viability of the solution. Some of the conditions set out in the offline algorithm such as capacity planning, distributions of paths, use of all links in a topology and reducing overloading of specific links are most particularly challenging to meet in random topologies. Thus, it is expected that once the offline algorithm is rendered for these topologies, online algorithm can apply the same method of inserting packets into the network as used in MPR and summarised in the following.

The proposed MSC-based approach applies a plane selection policy for each session to ensure a regulated traffic flow in the network enforced by the Ingresses (i.e. GW and ARs). In case of MSC, the cost of RPs are solely determined based on the available paths' bandwidth (bottleneck) and if there is more than one RP available, one RP would be selected randomly. In case of QMSC, when a packet arrives at an Ingress, the qualified RPs in terms of bandwidth are first selected. Subsequently the packet's classification is determined and its concerning Service Level Requirement (SLR) (i.e. jitter, latency, packet loss) is retrieved based on which the plane

selection policy is enforced. As a result, RPs that do not meet the required criteria for the concerning traffic class are removed and the most suitable RP with the lowest cost (as defined in [17]) is picked. At this point, in case of more than one RP being existent that meets the QoS criteria, the RP with the highest available bottleneck bandwidth is to be chosen. For both MSC and QMSC, once the qualified RP is selected, the packet is forwarded on the selected RP followed by the rest of the packets of the session.

## 5.4 Performance Evaluation

### 5.4.1 Online NS2-based Performance Analysis

We now proceed with presenting the performance in terms of various metrics that are analyzed by being averaged over snapshots throughout the simulation time based on the traffic types in Table 4.2. It is notable that, after offline plane selection based on our dynamic cost function, reverse engineering will be applied to associate each plane with an independent Dijkstra-based cost array (resulting in planes becoming distinguishable by MT-OSPF in the online mode becoming separate instances of OSPFs routing configurations).

TABLE IV illustrates the throughput for various traffic engineering strategies. The mean throughput is generally higher in case of MSC as compared with the other methodologies. This is due to the availability of a diverse set of routes across all the commodities that facilitates the splitting of traffic over several diverse RPs. Therefore, improved load balancing within the network is enabled through MSC. The smaller throughput in case of MPLS in comparison with MSC, is due to the lower diversity that causes a higher blocking of traffic. The blocking of a higher number of sessions in case of QMSC which is due to the enforcement of QoS criteria, causes a generally lower throughput in this case as compared with MSC and MPLS. It can also be observed that in the case of the throughput evaluation, there are variations in superiority of MSC TE, in some cases the benefits are 40% and more compared to other schemes while at some isolated instances they are not as impressive. The whole assessment on the adequacy

**Table 5.1:** Traffic types<sup>1</sup> and associated QoS requirements.

Traffic Class	Data Rate	Mean Duration	QoS requirements		
			Latency	Jitter	Packet loss
Class 1	Low ( $\approx 150$ Kbps)	180 sec	40-65 ms	0.5-2 ms	0.1-0.5 %
Class 2	Medium ( $\approx 250$ Kbps)	300 sec	4-5 s	<i>none</i>	5 %
Class 3	Low ( $\approx 128$ Kbps)	200 sec	300-600 ms	2 ms	5 %
Class 4	High ( $\approx 500$ Kbps)	360 sec	300 ms	30 ms	1 %
Class 5	Low ( $\approx 100$ Kbps)	90 sec	<i>no specific requirement</i>		

<sup>1</sup> Applications examples; Class 1 : VoIP, Class 2 : streaming video, Class 3 : streaming audio, Class 4 : interactive video, Class 5 : best effort data.

of MSC in random topologies is to be drawn after analysing all the result for all performance criteria/metrics, e.g. there is combination of gains and performance comparisons of MSC with other schemes. An accompanying observation for the throughput results is that for the case of large random topologies, distributions of topological interconnections and rendered paths in planes can be far from ideal in terms of the path distribution and a balanced use of the links. This is simply because the network can become very large in size and topologies are not suitably planned in terms of interconnections. Hence, benefits of intelligent multipath routing in terms of throughput can be less than expected in some instances of random topologies as there is possibility of bottleneck links that get too overloaded with traffic, which cause the online algorithm to be cautious and slower when inserting traffic in the network. A conclusion worth mentioning that was made in an outside study and can draw a parallel with this study of MSC, whilst being related to different types of networks and topologies [117] (e.g. fat-tree, ring and grid topologies for both intra/inter domain networks) and different types of packet flow distributions, states that there is limited gain to be achieved if the number of nodes in

certain network topologies is more than 25. While the study in this thesis is more focused on enabling control and desired use of networks resources in large random, and highly meshed, topologies, the extracted parallel is indicative of the unpredictability of situations and possible disruptions in expected performance gains when networks become significantly large in size (e.g. for T3 or T4 topologies as listed in Table 4.2).

The worse performance is observed in case of OSPF and InvCap methods which can be explained because of the availability of only one path between every Ingress-Egress pair. This would cause higher blocking and lower throughput. It should be noted that the divergence of results in case of OSPF and InvCap that use a similar strategy with different weight settings is because of different path-sets being rendered in case of these methods respectively as the networks are more random and have significant variations in shortest paths between ingress-egresses pairs. Moreover, it can be observed that the throughput is generally higher as the topology size increases in terms of links and nodes. This can be justified due to a relatively higher traffic volume being injected into the network thanks to a higher number of traffic Ingresses and a higher network capacity.

Blocking rate is defined as the number of sessions that have not been transmitted into the network relative to the sessions having been successfully delivered throughout the simulation time. The blocking rate is generally lower in case of MSC as observable from TABLE V. The higher path diversity in case of MSC facilitates the availability of a correspondingly higher number of paths that meet the minimum required bandwidth. The exertion of QoS criteria in case of QMSC for RP selection (which can cause a lack of available qualified path from the Ingress perspective) , leads to a generally higher blocking of sessions in comparison with MSC and MPLS especially towards the end of the simulations time when the network becomes heavily utilised and congested. Also, a similar discrepancy of the MSCs superiority can be observed as in the case of the throughput results that is ascribed to the same situation of excessive randomness of network topologies and limited ability of multipath routing to overcome bottleneck links. Hence, packet insertion in the network is more cautions and blocking increases (e.g. for

T3S1/2 topology cases, where network is extremely large with a lesser degree of interconnections/meshing, hence bottlenecks are more likely to occur). Meanwhile, the blocking in case of OSPF and InvCap is the highest due to a much fewer number of paths being available in these cases.

TABLE VI represents the end-to-end delay across the different topologies and strategies. With MSC and other multi-path strategies (i.e. QMSC, MPLS), multiple routes are available between every Ingress-Egress pair hence shortest-hop routes would no longer be used. Therefore, higher delays are experienced by the sessions forwarded onto the RPs. Regardless, the delay is still superior in case of MSC, and it is relatively lower in case of MSC for smaller topologies as the routes are generally shorter resulting in the delay being contained much better with higher throughput. As the topology size grows, the routes become relatively much longer and also more packets are delivered in case of MSC, MPLS and QMSC leading to a higher overall delay at the cost of a higher throughput and a smaller blocking rate. There is a trade-off between delivering more traffic with multi-path routing over longer paths, and increased average delay as discussed in [118], [119]. Therefore, more traffic is admitted with the gradual overflowing of network comparatively in case of multi-path routing. It can be also observed that end-to-end delay is generally lower in case of QMSC as compared with MSC and MPLS thanks to QoS enforcement and higher blocking. It is also notable that a generally higher delay is incurred with the rise of the network size. We should note that the delay in scoped access networks could be negligible in comparison with the delay emanating to and from the Internet. <sup>†</sup>

Packet loss rate represents the number of packets having been dropped relative to the ones having been successfully delivered throughout the simulation time. Packet loss occurs as a result of insufficient queue capacities caused by the increasing congestion in the network. The packet loss in case of the MSC method varies significantly and it is generally higher as it can be observed from TABLE VII. This can be justified by a higher amount of traffic being

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<sup>†</sup>as planes do not change for sessions once the first packet is admitted, there are no variations in packet delays in normal load situations and transport layers would not be disrupted

accommodated in the network in case of the MSC method as compared with the other approaches. Meanwhile, QMSC performs generally better than MSC and MPLS due to the QoS enforcement regulating the packet distribution into the network (resulting in a lower loss of sent packets). The loss rate is the lowest in case of InvCap and OSPF in general as a significantly smaller amount of traffic is accommodated within the network. Correspondingly, the loss rate is smaller in case of OSPF relative to InvCap as a smaller throughput is achieved as compared in case of OSPF. MPLS also performs better than MSC in most cases as less throughput is achieved relatively. Moreover, the loss rate is generally rising with the increase in the topology size as more traffic load is accommodated in case of larger topologies.

As it can be observed from TABLE VIII, the jitter rises significantly in case of MSC with the growth of the topology size as longer routes are traversed in case of MSC and higher traffic load is supported correspondingly resulting in a higher jitter. Jitter is lower in case of QMSC as compared with MSC while both outperform MPLS due to the QoS criteria being enforced at every Ingress. The rise in the supported traffic volume within the network in case of the multi-path approaches leads to a larger jitter especially for the larger topologies as compared with InvCap and OSPF, which is associated with more hops traversed by packets and longer routes.

**TABLE IV: Throughput (MB/s)**

Topology	OSPF	InvCap	MSC	QMSC	MPLS
T1S1	0.87	1.05	1.25	1.18	1.10
T1S2	0.68	0.90	1.40	1.27	1
T1S3	0.68	0.81	0.96	0.94	0.94
T2S1	1.75	2.39	4.23	3.90	3.99
T2S2	0.84	2.68	4.16	4.248	4.242
T2S3	2.24	1.99	4.36	3.31	3.97
T3S1	2.57	4.31	6.35	5.77	6.11
T3S2	3.16	4.43	7.65	7.41	8.82
T3S3	3.34	3.78	7.99	7.39	7.29

**TABLE V: Blocking (%)**

Topology	OSPF	InvCap	MSC	QMSC	MPLS
T1S1	11.46	10.68	0.68	0.76	0.85
T1S2	31.92	9.12	0.59	1.1	2.72
T1S3	31.92	31.92	31.02	31.64	31.03
T2S1	25.25	9.27	4.72	5.8	5.47
T2S2	64.56	28.12	14.31	13.65	8.10
T2S3	9.79	18.28	1.14	3.56	2.74
T3S1	34.90	46.98	26.72	28.1	27.12
T3S2	38.83	38	24.63	23.50	21.40
T3S3	34.75	49.47	24.04	24.61	25.27

**TABLE VI: Delay (ms)**

Topology	OSPF	InvCap	MSC	QMSC	MPLS
T1S1	10.15	6.04	2.58	2.19	5.63
T1S2	15.80	3.85	3.51	2.45	4.03
T1S3	15.80	16.01	13.93	11.30	13.98
T2S1	12.57	6.33	8.26	3.28	5.68
T2S2	131.33	25.54	60.02	37.84	60.34
T2S3	5.25	10.33	6.37	2.65	3.02
T3S1	6.01	6.01	22.41	15.23	20.73
T3S2	42.26	21.37	179.87	110.85	192.95
T3S3	30.37	86.94	165.42	91.72	201.53



**TABLE VII: Packet Loss Rate (%)**

<b>Topology</b>	<b>OSPF</b>	<b>InvCap</b>	<b>MSC</b>	<b>QMSC</b>	<b>MPLS</b>
T1S1	0.00025	0.04	0.09	0.01	0.015
T1S2	0.035	0.05	0.14	0.022	0.033
T1S3	0.038	0.04	0.001	0.008	0.01
T2S1	0.02	0.04	0.13	0.05	0.12
T2S2	0.51	0.02	0.13	0.13	0.37
T2S3	0.05	0.05	0.17	0.0005	0.006
T3S1	0.2	0.91	1.85	0.06	0.12
T3S2	0.038	1.09	2.76	1.65	3.33
T3S3	0.04	0.05	3.33	1.66	2.95

**TABLE VIII: Jitter (ms)**

<b>Topology</b>	<b>OSPF</b>	<b>InvCap</b>	<b>MSC</b>	<b>QMSC</b>	<b>MPLS</b>
T1S1	23.83	12	0.84	0.2	11.72
T1S2	30.33	5.21	3.27	0.22	6.66
T1S3	30.33	30.30	26.46	22.60	26.47
T2S1	20.31	11.29	13.80	3.07	9.23
T2S2	159.78	38.50	85.56	74.02	104.03
T2S3	8.83	17.95	7.40	1.09	1.22
T3S1	115.42	74.80	103.64	85.86	111.67
T3S2	73.89	35.46	194.28	152.33	204.09
T3S3	51.38	111	184.13	130.22	205.56

## 5.5 Summary

In this chapter, a novel MSC-based TE approach has been proposed that suits the future random all-IP access network structures. The unpredictable and expected disparate nature of access network structures as reflected in the evolutionary access networks, in conjunction with the rise of IP-based real-time applications calls for a novel adaptive routing optimization paradigm. To this end, a comprehensive MSC-based TE mechanism applicable to random access network structures comprising an offline and an online TE mechanism is put forward. This mechanism allows the network to maintain a set of path-diverse independent logical topologies which can be used to balance the traffic load in the network. The RPs represent multiple OSPF topology instances with the aim of achieving path diversity with minimal extra protocol overhead. Due to the NP-complete nature of MSC and application of multiple QoS metrics for different traffic types, heuristics have been adopted for both the offline RP construction and online TE solution. Our offline approach adopts a dynamic minimum set-cover based cost function in order to construct a path-diverse set of RPs while also considering capacity. The offline RP construction output demonstrates the effectiveness of our approach by creating a diverse set of RPs for a wide-ranging set of randomly generated graphs of different sparseness/meshing levels where the legacy MPR's TE mechanism is redundant. Furthermore, under a practical NS2-based online traffic flow model, it has been demonstrated that our MSC-based approach outperforms the rival strategies namely MPLS, OSPF and InvCap in extensive complex randomly shaped access networks.

In the next chapter, conclusions on this thesis will be laid out followed by elaborations on possible extensions of this research as future work.

# 6

## Conclusions and Future Work

### 6.1 Conclusions

All-IP access networks increasingly relevant structures and their associated practical architectures along with routing optimization challenges were investigated extensively in this thesis. The architectural evolution of convergent all-IP access networks as also reflected in the trends towards a flat-IP structure and novel backhaul structures that have recently been highlighted as the great challenges in proliferations of new generations of networks. Along with the exponentially rising IP-based real-time applications there is a surging demand for consistent adaptations in the routing optimization approaches. Correspondingly, the thesis provided a description on how MPR which consolidates various aspects in all-IP infrastructure and offers diversity facilitated by the network maintaining several independent logical topologies, is extended, remodelled and modified to become adaptive in line with some increasingly relevant architectures, structures and practical applications. Aspects of the evolutions of IP-based access networks via convergences of cellular and Internet-based networks have been described and applied in the work as its foundations.

Another background to development of MPR is in extensive work on advancements of TE schemes for various types of networks, with a vast number of proposed solutions and their

lines of classifications. Despite these multitudes of proposals there is still a lacking of a major breakthrough in terms further adoptions of solutions beyond the initial protocols that have remained operational and unchanged for quite some time now. Being facilitated by multiple OSPF topology instances in networks that are controlled by offline and online algorithms, MPR achieves path diversity with minimal extra protocol overhead relative to rival strategies. To this end, the rendered diversity facilitates network wide load balancing and is fitted to a wide range of topological configurations as ratified through investigation. Heuristics were applied for both offline and online TE mechanisms respectively, because of the NP-complete nature of finding suitable RPs in diverse practical fixed and random topologies, and use of multiple QoS metrics for realistic traffic types to be supported by networks routing. Moreover, MPRs legacy offline approach inapplicability to randomly shaped access network structures (random graphs) inspired the introduction and adaptation of a novel MSC-based approach for the problem of building multiple RPs in Chapters 4 and 5.

Initially in chapter 3, the remodelled IP TE-based MPR in terms of both its offline and online approaches (in line with the developing access network architectures) was investigated. To this end, two cases that are reflective of the evolution in the access network architecture designs have been studied in terms of various metrics under fluctuating internal/external traffic distributions to mimic a comprehensive realistic traffic scenario that facilitates a comprehensive performance evaluation. Coupled with the verification of MPR-based methods superiority over legacy OSPF/InvCap methods, it has also been shown that the flat-IP based design concept (case II) outperforms the hierarchical-based concept (case I). Moreover, the rise in the internal traffic ratio has rendered performance degradation under both network architecture design concepts but has improved in line with increased meshing in the networks in general. Furthermore, MPR has been extended to support the revolutionary Tactile Internet. To this end, a reliable novel routing policy has been outlined in order to cater for Haptics communication effectively over all-IP access networks. It has been demonstrated that the TAP policy performs well for different levels of congestion. It has also become apparent that shortest-path solutions such as

OSPF cannot be used in order to handle Haptic communications in typical Internet network topologies. In chapter 4, the problem of building multiple paths-diverse RPs in random graphs (i.e. legacy MPRs offline TE limitation) has been addressed. To this end, IP TE-based MPR has been extensively redesigned and reformulated to suit the future randomly shaped all-IP access network structures. The variable and disparate nature of access network structures as reflected in the evolutionary access networks, along with the rise of IP-based real-time applications demand a new consistent routing optimization paradigm. To this end, a comprehensive TE mechanism applicable to random access networks was proposed. This mechanism allows the network to maintain a set of diverse independent logical topologies which can be used to balance the traffic load in the network. Our approach adopts a dynamic minimum set-cover based cost function in order to construct a diverse set of RPs while also considering capacity. The offline results demonstrate the effectiveness of our approach by creating a diverse set of RPs for a wide-ranging set of randomly generated graphs (random graphs) of different sparseness levels where the legacy MPRs TE mechanism is redundant.

By design, essential features of MSC which are integrated in its offline algorithm enable adaptability to any random topological structures which can correspond to any real world access network. To this end, MSC intelligently distributes the paths between Ingresses and Egresses in the network based on the identified essential criteria for IP access networks. Therefore, the adaptability and flexibility of MSC is derived by the algorithmic features that use the networks routing resources in the most efficient manner through planning link utilisations (resonated by paths correlation and capacity projections). This represents a novel offline TE approach and is independent of how networks are composed. As noted for MPR that falls short in handling random topologies due to its rigid and insufficient offline algorithm based on link weights and not direct manipulation of graphs as in MSC, other schemes such as MPLS and OSPF do equally lack specifically tailored features to address random and unpredictable topological setups.

Notably, the performances of the plane constructing, spanning tree algorithms from Chap-

ter 4 have in fact been integrated in the offline simulations. These algorithms have rendered the desirable RP sets for topologies with 7 nodes in our simulations. However, for the rest of the topologies, due to the computational complexity associated with the graph based algorithms, the greedy algorithm i.e. hill climbing has been applied as a complementary solution to obtain a close to optimum set of planes based on the offline algorithm criteria. In a summary, the proposition of the novel MSC offline algorithm that solves the problem of routing plane construction for large random topologies are needed for: 1) solving random meshing in graphs in smaller topologies; 2) providing the tools for understanding and applying the algorithmic approximation via hill climbing in case of grand topologies; and, 3) enabling a methodology for deriving costs in the process of selecting routing planes in all cases.

Under a practical NS2-based online traffic flow model, it has been demonstrated in Chapter 5 that our proposed MSC-based approach outperforms the rival strategies namely MPLS, OSPF and InvCap in extensive complex randomly shaped access networks in most cases. It can be also concluded that as we use random walk to build very random topologies, the performance of MSC could be affected due to possible topological disorders namely some links getting heavily loaded. Additionally, the complementary online results further underscore the effectiveness of our MSC-based approach in case of random access networks. It is also noted that despite the MSCs superior performance due to its ability to adapt to and utilize various random topologies, in real scenarios, there is a limit to how much an overly random and unplanned structure of a network can be exploited with certainty. This point is underlined in Chapter 5 where for some topology cases, e.g. less meshed T3Sx topology, there are oscillations in performance benefits of MSC and for cases of 60 node topologies the results have not been shown due to similar variations. These variations can happen due to the extremely random setups of links in networks causing a situation of a high link overload, that is, a bottleneck, where it is not reasonable possible to always provide huge performance benefits by load balancing via satisfactory levels of path diversity. Regarding general aspects of performance evaluations, MSC is generally expected to behave favourably in scenarios of high link utilisations that happen when traffic

demands are high. In other words, MSC extends the threshold at which packet losses occur in the network, hence facilitating a higher throughput potential in the network. There remain challenges that need to be investigated and addressed in order to facilitate the adaptation of a practical paths-diverse near optimum approach in future access network structures. Moreover, this approach can be further optimized for improved performance and presented as a complete practical solution once other proposed aspects have been fully investigated. To this end, in what follows, other possible extensions and adaptations have been identified and presented.

## 6.2 Future Work

Similar to any other technique during its first years of development, the methods introduced in this thesis still have a lot of room for improvement before they can be adopted as a fully viable routing optimization scheme in future all-IP access networks.

The proposed algorithms' time complexity performance can be optimized by taking into account Polynomial time approximation (e.g. in case of multiple QoS constrains). In consideration of the various QoS criteria associated with different traffic classes, we have considered several QoS constrains in our approaches throughout this thesis which can be compared and optimized against the best-known algorithm designed for this special case [120].

As another extension, weight re-setting and hence paths' re-configuration at different online traffic flow intervals can be introduced, facilitated through the constant collaboration of offline and online TE methods. SDN's feature of programmability of routers can be adopted as the enabler of this collaboration, eliminating the overhead associated with paths' re-configurations. Comparisons can be drawn against OSPF, MPLS and ECMP in terms of various performance criteria and overhead. Moreover, a new cost function providing a comprehensive quantitative comparative indication of performance of these rival solutions in access networks can be developed. Such a cost function could quantify the cost of all these rival approaches by considering bottleneck bandwidth and QoS metrics in addition to overhead, reconfiguration time and time

complexity.

Authors in [121] argue that a huge economic cost could result if QoS metrics namely packet loss, jitter and delay are not met in the backdrop of the rising variant traffic types. Therefore, a cost function that takes into account the economic benefits of serving Tactile packets efficiently in presence of other traffic classes can be developed . For comprehensiveness, the varying percentage of the potential Tactile traffic in a given scoped access network can also be considered in conjunction. Extended traffic models and more traffic variations with application of feedbacks for Tactile Internet in random networks can be considered. In addition to the packet duplication method, other intelligent and selective packet distribution and prioritization strategies along with more advanced queuing models could also be taken into consideration.

Another interesting consideration could be the application of real network trace data from metropolitan access networks (e.g. Rocketfuel, Metronet UK) so that the performance of our proposed MSC- based approach could be evaluated and validated. A real-world 5G-like network test-bed would also prove to be highly valuable as it would allow for the quantification of the processing overhead caused by our approach on edge-routers in an increasingly dense access environment and can be compared with an identical MPLS setup.



# **Appendices**

# Appendix A

## Online TE Approach

Routing in a network can be represented as a multi-commodity flow problem with multiple flow demands associated with different *Ingress* and *Egress* nodes for each plane. A flow demand corresponds to IP sessions, and once a plane is chosen it remains unchanged for duration of the session.

$$\sum_{v:(u,v) \in \mathcal{E}} f_{(uv)P_n^d}^\delta - \sum_{v:(v,u) \in \mathcal{E}} f_{(vu)P_n^d}^\delta = \begin{cases} d_u^\delta, & \text{for } u = s \\ 0, & \text{for } u \in V - \{s, t\}, \\ -d_u^\delta, & \text{for } u = t \end{cases} \quad (\text{A.1})$$

$$f_{uv} = \sum_{\delta \in \mathfrak{D}} f_{uv}^\delta \leq c_{uv} \quad \forall (u, v) \in \mathcal{E} \quad (\text{A.2})$$

$$f_{uv}^\delta \geq 0 \quad \forall \delta \in \mathfrak{D}, \forall (u, v) \in \mathcal{E} \quad (\text{A.3})$$

where  $d_u^\delta$  represents the amount of traffic contributed to the network by node  $u$  for commodity  $\delta$ . (A.1) signifies the flow conservation constraints and (A.2) represents the capacity constraints. We keep the objective of achieving a practical maximum use of diverse network topological configurations/RPs facilitated by the offline algorithm. The options of paths subject to every RP layout are cumulatively considered through online decisions made at *Ingress/source*.

To this end, we consider the application of heuristics namely MPR and its extension QoS-aware MPR (QMPR) in a multi-commodity flow scenario. MPR's online TE approach was initially introduced in [63]. As opposed to the previously considered singular source case, we have adopted a realistic online traffic scenario where both the GW and the ARs can be sources and destinations of traffic simultaneously giving rise to the breakdown of traffic to internal and external nature. Additionally, we put forward a more complete formulation of MPR's online routing complemented with an optimization framework.

In the network; a set of users is defined as  $\mathcal{B} = \{b : b = 1, \dots, B\}$ .  $\mathcal{T} = \{t : t = 1, \dots, T\}$  indicates the set of traffic types.  $\mathcal{Q} = \{q : q = 1, \dots, Q\}$  represents the set of sessions whereas  $m_q$  signifies the additive QoS metrics associated with every session  $q$ .  $c_q^t$  is defined as the QoS constraint of session  $q$  associated with traffic type  $t$ .  $\Pi^{b,d}$  indicates the traffic rate associated with user  $b$  and demand  $d$ .  $\|\Pi^{b,d}\|_0$  signifies the non-zero non-negative entries of  $\|\Pi^{b,d}\|$ . MPR applies a plane selection policy for each session to ensure a regulated traffic flow in the network. This policy is enforced by the sources (i.e. GW and ARs). In case of MPR, the cost of RPs are solely determined based on the available bandwidth and if there is more than one RP available, one RP is selected randomly. In case of QMPR, when a packet arrives at a source, the qualified RPs in terms of bandwidth are first picked out, subsequently the packet's classification gets verified and hence its associated Service Level Requirement (SLR) (i.e. jitter, latency, packet loss) is obtained based on which the plane selection policy is applied. Consequently, RPs that do not meet the required criteria for the concerning traffic class are pruned and the most suitable RP with the lowest cost is selected. At this stage, in case of the existence of more than one RP that meets the QoS criteria, the RP with the highest available bottleneck bandwidth is selected. In case of both MPR and QMPR, once the qualified RP is selected, the packet is forwarded on the chosen RP followed by the rest of the packets of the session (Online pseudo-code is presented in **Algorithm 4**). The cost function for any path  $p_n^d$  is represented as follows as a

summation of real time costs of each link in the path:

$$\begin{aligned} \Phi_{\Gamma}^t(p_n^d) = & \Psi \cdot \sum_{uv \in P_n^d} \sum_{q \in Q} R_{uvP_n^d}^d \left( \frac{m_q(uv)}{c_q^t} \right) \cdot \gamma_q \\ & + Y \cdot \left( \frac{b(p_n^d) - \|\Pi^{b,d}\|_0}{C(b(p_n^d))} \right)^{-1} \end{aligned} \quad (\text{A.4})$$

Where  $\gamma_q \in [0, 1]$  is the binary factor used to associate session  $q$  with its QoS requirements.  $b(p_n^d)$  represents the available bandwidth on path  $p_n^d$ . The available bandwidth is calculated by taking into consideration the bottleneck on every path at various instances:

$$\begin{aligned} b(p_n^d) = & \min_{(e_{uv,n}) \in p_n^d} b(e_{uv,n}) \\ \text{Where: } & \{e_{uv} | (u, v) \in \mathcal{V}^2, \forall u \neq v, \forall n \in \mathcal{N}\} \\ & b(p_n^d) = \{b(e_{uv,n}) | (e_{uv,n}) \in p_n^d, \forall n \in \mathcal{N}\} \end{aligned} \quad (\text{A.5})$$

$\Psi$  is the binary factor which is 1 when any path  $p_n^d$  meets the minimum bottleneck requirement as outlined above.  $Y$  symbolises the binary variable which is equal to 1 in case of both the QoS and bottleneck requirements are met for more than one candidate RP hence the one with the highest bottleneck bandwidth is selected. We formulate our optimization problem based on the general OSPF TE optimization framework proposed in [118]. MPR's online TE aims to maximize throughput while routing the traffic through the optimum path taking into account the associated cost which is sought to be minimised along with the traffic rate on every path on the RP set available. Our MPR-based formulation takes into account the existence of different types of traffic in the network whereas access to multiple paths is facilitated through the offline RP construction TE approach.

$$\begin{aligned}
& \max \quad \sum_{q \in Q} \alpha_q \Phi_q - \sum_{q \in Q} \sum_{p_n^d \in \mathcal{P}_{\mathcal{N}}} \phi_{\Gamma}^t(p_n^d) \|\Pi^{b,d}\|_0 \\
& \text{s.t.} \quad \|\Pi^{b,d}\|_0 \leq b(p_n^d) \\
& \quad m_q(p_n^d) \equiv \sum_{e_{u,v}, n \in p_n^d} m_q(e_{u,v}, n) \leq c_q^t \\
& \quad \forall d \in \mathcal{D}, \forall b \in \mathcal{B}, \forall n \in \mathcal{N}, \forall t \in \tau, \gamma_k \in [0, 1]
\end{aligned} \tag{A.6}$$

Where throughput of session  $q$  associated with any user and demand on path  $p_n^d$  is:  $\Phi_q = \sum_{p_n^d \in \mathcal{P}_{\mathcal{N}}} \|\Pi^{b,d}\|_0$ .  $\alpha_q$  represents the optimum path for every session considering its associated cost. The constraints ensure the validity of the path in terms of meeting the minimum bottleneck requirement in addition to the QoS requirements associated with the corresponding session.

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**Algorithm 4** Online Plane Selection Algorithm

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1: **procedure** POLICY-PS

2: Packet arrives at *Ingress*  $AR_a/GW$  destined for *Egress*

3: **If**  $\|\Pi^{b,d}\|_0 \leq b(p_n^d)$ , for at least  $n \in \mathcal{N}$  **then**

4: Admit the session

5: Conduct lookup for the associated traffic class  $t \in \tau$

6: Ascertain QoS requirements  $c_q^t$  for traffic class  $t$

7: Remove all RPs in  $\mathcal{N}$  that do not satisfy SLRs for each  $q \in Q$  and retrieve set  $\mathcal{CP}$

8: Calculate cost for each RP

$$\begin{aligned}
\phi_{\Gamma}^t(p_{cp_i}^d) = & \Psi \cdot \sum_{uv \in p_n^d} \sum_{q \in Q} R_{uv p_n^d}^d \left( \frac{m_q(uv)}{c_q^t} \right) \cdot \gamma_q \\
& + Y \cdot \left( \frac{b(p_n^d) - \|\Pi^{b,d}\|_0}{C(b(p_n^d))} \right)^{-1}
\end{aligned}$$

9: Select RP  $cp_1$  with the lowest cost  $\phi_{\Gamma}^t$  for the incoming session given:  $\phi_{\Gamma}^t(cp_1) \leq \phi_{\Gamma}^t(cp_2) \leq \dots \leq \phi_{\Gamma}^t(N - \bar{\mathcal{CP}})$

10: **else** Reject session

11: **end if**

12: **end procedure**

---

## Appendix B

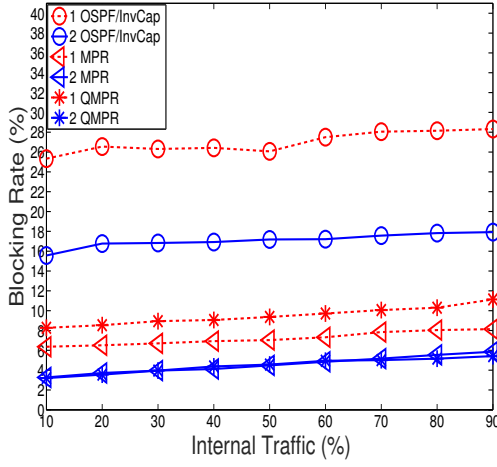
# Performance under Realistic NS2-based Simulations

### Blocking Rate (%)

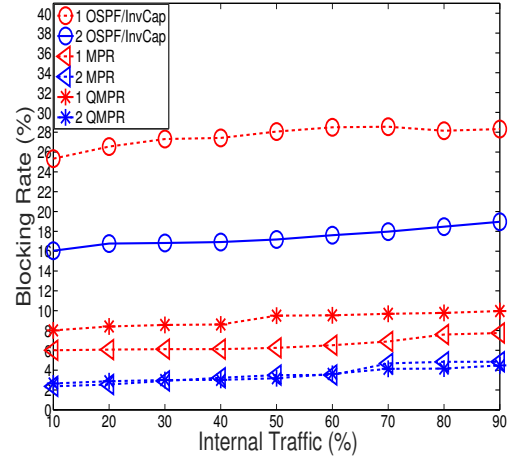
The rendered mean session blocking rate, as observed in Figure B.1, is lower in Case II in comparison with Case I as the bottleneckness of the entire traffic traversing the GW has been avoided. The blocking rate for the MPR-based methods is lower due to higher path diversity as compared to the OSPF/InvCap methods where a much fewer number of paths are available. As compared with MPR, the blocking rate for QMPR is slightly higher in both Case I and II. This indicates that the enforced QoS requirements have rendered greater blocked traffic. Moreover, the mean blocking rate has consistently increased for all the methodologies across the topologies in line with the intensification of the internal traffic distribution. It can be also observed that blocking is generally higher in case of the second topology-set (i.e.  $T_2M_1, T_2M_2$ ) as the traffic flow distribution is different. This is due to the comparatively higher traffic load on the network incurred by more traffic sources in spite of the larger network size. The blocking has declined across both of the topology-sets in line with the increase in meshing as a higher number of links and RPs become available in consequence, to route the traffic \*.

---

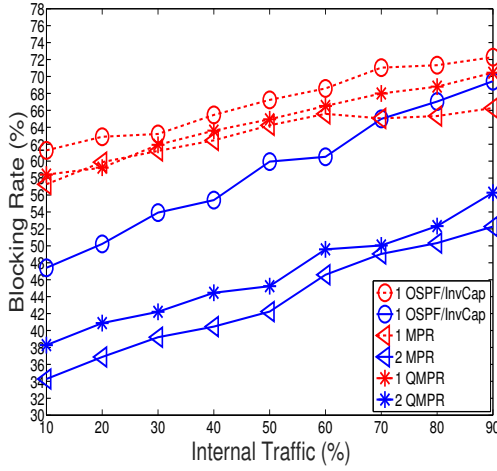
\*This behavior intuitively suggests that as networks become randomly larger in size and includes more traffic sources, the transient space should increase (routers and meshing) accordingly to accommodate the demands



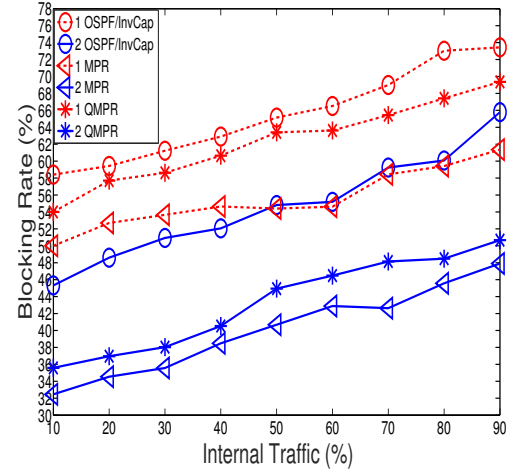
(a)



(b)



(c)



(d)

**Figure B.1:** Blocking Rate (%); a)  $T_1M_1$  b)  $T_1M_2$  c)  $T_2M_1$  d)  $T_2M_2$

### Packet Loss Rate (%)

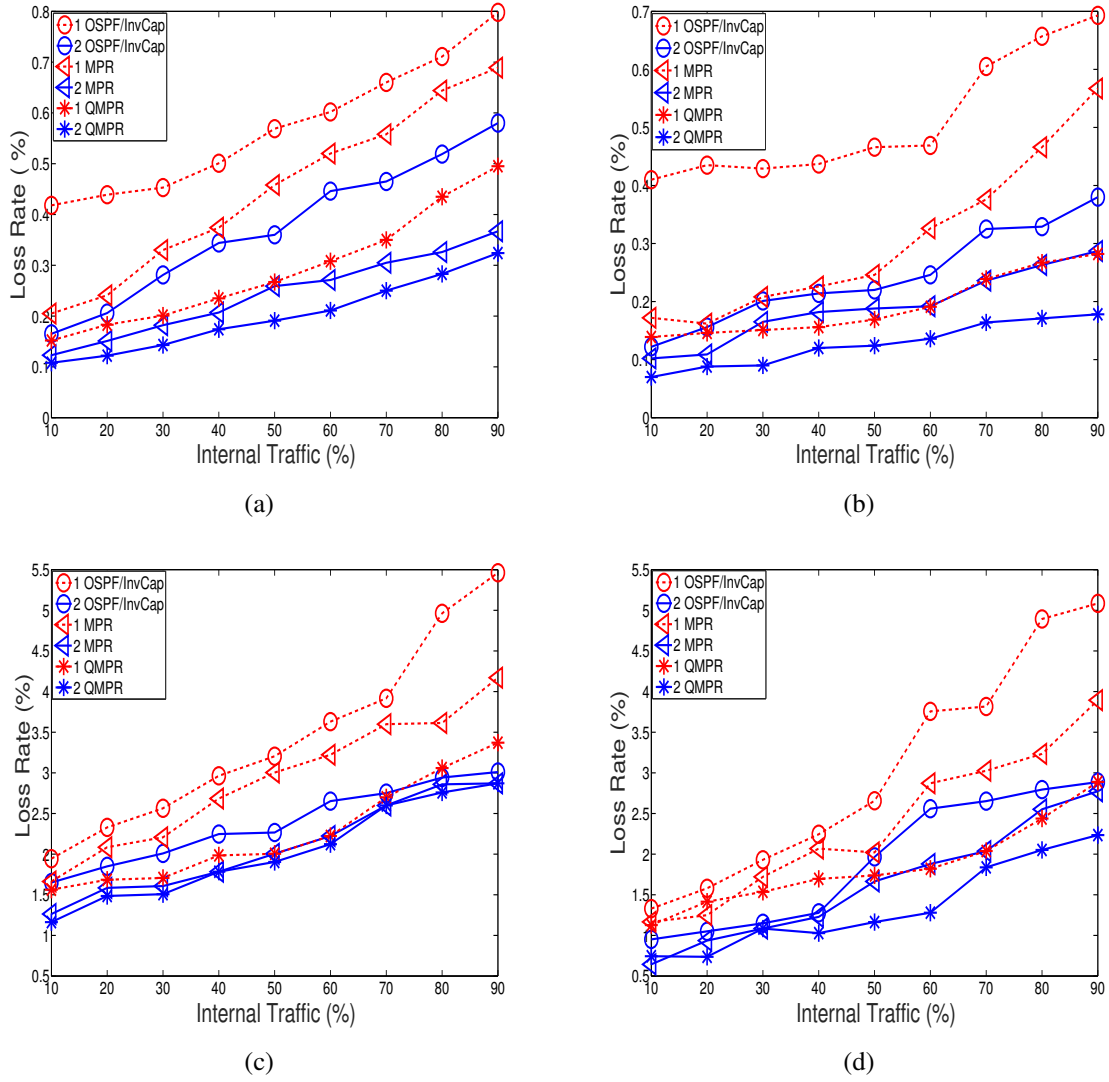
Packet loss occurs due to insufficient queue capacities caused by increasing congestion in the network. As observed in Figure B.2, the rendered average packet loss rate is lower in Case II than Case I. This is due to higher congestion and blocking triggered by less path diversity for traffic sources in case I (where the entire traffic passes through the GW), having led to the loss of more packets. The loss rate in case of the MPR-based methods is lower due to the higher path diversity for the incoming sessions as compared with OSPF/InvCap. QMPR outperforms MPR in terms of loss rate as the packet distribution into the network is regulated based on

the QoS requirements, hence resulting in a lower loss of sent packets. With the intensification of the internal traffic distribution, the loss rate has increased correspondingly across all the topologies. This is due to the higher congestion caused by the lack of residual capacity relative to the surging internal traffic demand throughout the network. It can be also observed that the packet loss rate declines as the meshing increases across both of the topology-sets since more links and RPs become available with the rise in meshing. Moreover, a generally higher loss rate has occurred in case of the second topology in which the traffic flow distribution model is different due to the comparatively higher traffic load on the network incurred by more traffic sources.

### **Delay (ms)**

As can be observed from Table B.1 and Table B.2, a higher mean delay is incurred with Case I as longer routes are traversed as compared to Case II. Furthermore, a lower queuing delay occurs in case II due to the higher path diversity available for sources of traffic as opposed to Case I where the entire traffic passes through the GW. This leads to the accelerated queue processing in Case II. A higher delay is incurred in the MPR-based methods as shortest-hop routes are not always used and more traffic is delivered. It was shown in [118] that for OSPF TE, the price for a higher throughput facilitated by multiple available paths is the heightened average delay caused by growth in the average path length. It was also shown in [119] that as demand surpasses a certain amount, delay would be correspondingly higher as more traffic is delivered in the case of multi-path routing. Moreover, in both cases, delay has increased with the rise in the internal traffic distribution. This is the consequence of the higher traffic density having led to longer queue processing times, and a higher overall number of hops having been traversed. It can be also observed that the delay in the case of the second set of topologies is higher, as the network is larger in terms of nodes and links, with a higher traffic density. The results demonstrate a general decline in delay in line with the rise in meshing across both of the topology-sets. This is thanks to the availability of more links and RPs helping





**Figure B.2:** Packet Loss Rate; a)  $T_1M_1$  b)  $T_1M_2$  c)  $T_2M_1$  d)  $T_2M_2$

to lower the congestion in the network, in consideration of the average delay on every link being largely dependent on its residual capacity based on the well-known Kleinrock independence approximation [122]. Therefore, it can be concluded that the increase in meshing facilitates a better distribution of traffic and a consequential reduction in queuing times that results in a lower overall delay.

**Table B.1:** Delay (ms) for the first topology

Traffic	OSPF/InvCap				MPR				QMPR			
(%)	Case I		Case II		Case I		Case II		Case I		Case II	
	$T_1M_1$	$T_1M_2$	$T_1M_1$	$T_1M_2$	$T_1M_1$	$T_1M_2$	$T_1M_1$	$T_1M_2$	$T_1M_1$	$T_1M_2$	$T_1M_1$	$T_1M_2$
10	4.82	4.82	3.94	3.94	12.01	10.03	10.00	9.65	11.26	9.96	10.06	7.06
20	5.03	5.03	4.03	4.03	12.22	10.27	10.46	9.74	11.70	10.20	10.38	7.37
30	5.23	5.23	4.11	4.11	12.63	10.54	11.01	10.04	11.84	10.22	10.49	7.49
40	5.43	5.43	4.32	4.32	12.81	10.76	11.22	10.26	12.01	10.27	10.65	7.65
50	5.46	5.46	4.56	4.56	13.39	11.47	11.56	10.47	12.21	10.30	10.89	7.89
60	5.92	5.92	4.78	4.78	13.56	11.62	11.84	10.95	12.55	10.35	10.10	8.10
70	6.01	6.01	4.80	4.80	13.75	11.85	12.41	11.01	12.86	10.52	10.35	8.35
80	6.54	6.54	4.85	4.85	13.96	11.95	12.21	11.20	12.94	10.88	10.54	8.54
90	6.84	6.84	4.87	4.87	15.02	12.02	12.56	11.37	13.59	11.03	10.83	8.83

**Table B.2:** Delay (ms) for the second topology

Traffic	OSPF/InvCap				MPR				QMPR			
(%)	Case I		Case II		Case I		Case II		Case I		Case II	
	$T_2M_1$	$T_2M_2$	$T_2M_1$	$T_2M_2$	$T_2M_1$	$T_2M_2$	$T_2M_1$	$T_2M_2$	$T_2M_1$	$T_2M_2$	$T_2M_1$	$T_2M_2$
10	81	81	48	48	159.8	152.1	109.4	100.5	138.5	129.5	92.5	80.1
20	81.4	81.4	48.3	48.3	160.4	152.8	109.6	100.5	139.8	129.8	92.8	80.8
30	81.8	81.8	48.8	48.8	161.3	153.1	110	100.6	140	130	93	81
40	82.3	82.3	49	49	162	153.8	110.3	100.6	140.5	130.6	93.1	81.2
50	82.7	82.7	49.3	49.3	162.7	154.2	110.8	101.1	140.8	131	93.4	81.6
60	83	83	49.7	49.7	163.6	154.8	111	101.3	141.3	131.2	93.8	81.7
70	83.5	83.5	50	50	164.7	155	111.3	101.7	141.7	131.9	94.1	82
80	83.8	83.8	50.2	50.2	165.3	155.7	111.8	102	142.3	132.2	94.5	82.7
90	84.2	84.2	50.4	50.4	165.9	156.3	112	102.1	142.8	132.8	95.3	82.9

## **Appendix C**

### **Tactile Aware Policy**

---

**Algorithm 5** Tactile Aware Policy

---

```
1: procedure E-POLICY-PS( $P_n^d, \tau, \kappa, \mathcal{N}, V$ )
2:   packet arrives at the Ingress  $r \in V$  destined to the Egress  $g \in V$ 
3:   if packet does not belong to an existing session (i.e. new session) then
4:     Perform lookup and check traffic class  $t \in \tau$ 
5:     Obtain QoS requirements  $c_k^t$  for traffic class  $t$ 
6:     if  $|\pi^{b,d}| \leq b(p_n^d)$ , for at least one  $n \in \mathcal{N}$  then
7:       Session is admitted
8:       if the arrived packet  $\in$  tactile traffic class then
9:         Add packet to the priority class.
10:        Generate a duplicate of the concerning packet
11:        Add duplicate packet to the priority class
12:        Select RP  $x_1$  with the lowest cost  $f(x)$  and  $x_2$  with the second lowest cost
         $f(x)$  for the session associated with user  $u$  given:  $f(x_1) \leq f(x_2) \leq \dots \leq f(N - \bar{X})$ .
13:        Route the original packet by using  $x_1$  and the duplicate through  $x_2$ .
14:      else
15:        Add packet to the non-priority class.
16:        Select RP  $x_i$  in a random manner
17:        Route the packet through  $x_i$ .
18:      end if
19:    else
20:      Reject Session
21:    end if
22:  else
23:    Add packet to the same class as the previous ones that are part of the same session
24:    Route packet by using the already assigned RP to the previous packets that belong
    to the same session
25:    if arrived packet  $\in$  tactile traffic class then
26:      Generate a duplicate of the concerning packet
27:      Route the duplicate by using the already assigned RP to the previous duplicates
      that belong to the same session
28:    end if
29:  end if
30: end procedure
```

---

## Appendix D

### Performance Results for Tactile Internet

**Table D.1:** Traffic types<sup>1</sup> and associated QoS requirements.

Traffic Class	Data Rate	Mean Duration	QoS requirements		
			Latency	Jitter	Packet loss
Class 0	Low ( $\approx 150$ Kbps)	180 sec	1 ms	20 $\mu$ s	0.00001 %
Class 1	Low ( $\approx 150$ Kbps)	180 sec	40-65 ms	0.5-2 ms	0.1-0.5 %
Class 2	Medium ( $\approx 250$ Kbps)	300 sec	4-5 s	<i>none</i>	5 %
Class 3	Low ( $\approx 128$ Kbps)	200 sec	300-600 ms	2 ms	5 %
Class 4	High ( $\approx 500$ Kbps)	360 sec	300 ms	30 ms	1 %
Class 5	Low ( $\approx 100$ Kbps)	90 sec	<i>no specific requirement</i>		

<sup>1</sup> Applications examples; Class 0 : haptics, Class 1 : VoIP, Class 2 : streaming video, Class 3 : streaming audio, Class 4 : interactive video, Class 5 : best effort data.

Topology	OSPF	Optimal	TAP
$T_1M_1$	47.6274	0.818168	0.889203
$T_1M_2$	47.6274	0.80454	0.875463

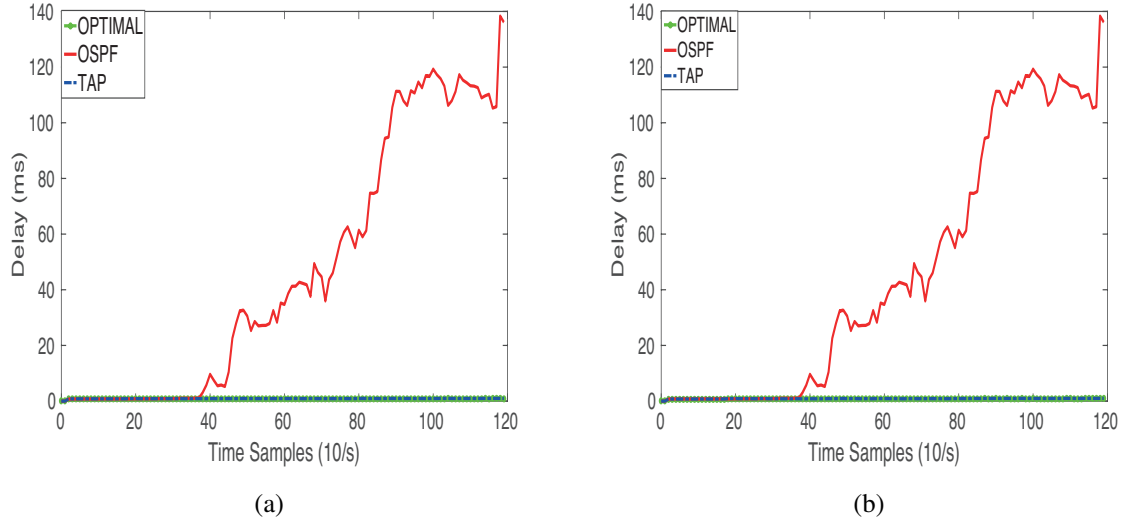
**Table D.2:** Average delay (*ms*)

### Delay (ms)

We use Table D.2 to present our data because the difference between the optimal case and TAP is not possible to be visualised with graphs. As it can be observed from Table D.2, the  $T_1M_2$  topology has a slightly better performance in terms of the expected delay as  $T_1M_2$  has more links compared to  $T_1M_1$ . Consequently, the traffic can be distributed better over the network due to the existence of more RPs; therefore, the mean delay will be reduced as the queues are less cramped and longer routes do not affect the delay. As expected, TAP performs to some extent worse than the optimal. The main reason behind this difference is the fact that a non-priority packet being served while a priority packet arrives at the empty priority queue. In this case, extra queuing delay will be added to the priority packets leading to an increase in the expected delay. In general, TAP performs extremely well in terms of delay even when the traffic congestion in the network is very high. To be more specific, the delay would never exceed the threshold of 1 ms. On the other hand, as illustrated in Figure D.1, plain vanilla of OSPF cannot support haptics communication due to the high values of delay incurring cyber sickness to Tactile applications. The main reason behind the big difference between OSPF and TAP is that OSPF does not facilitate any priority for the packets that belong to the Tactile class in addition to the lack of diversity. Consequently, the queueing delay will be extremely high.

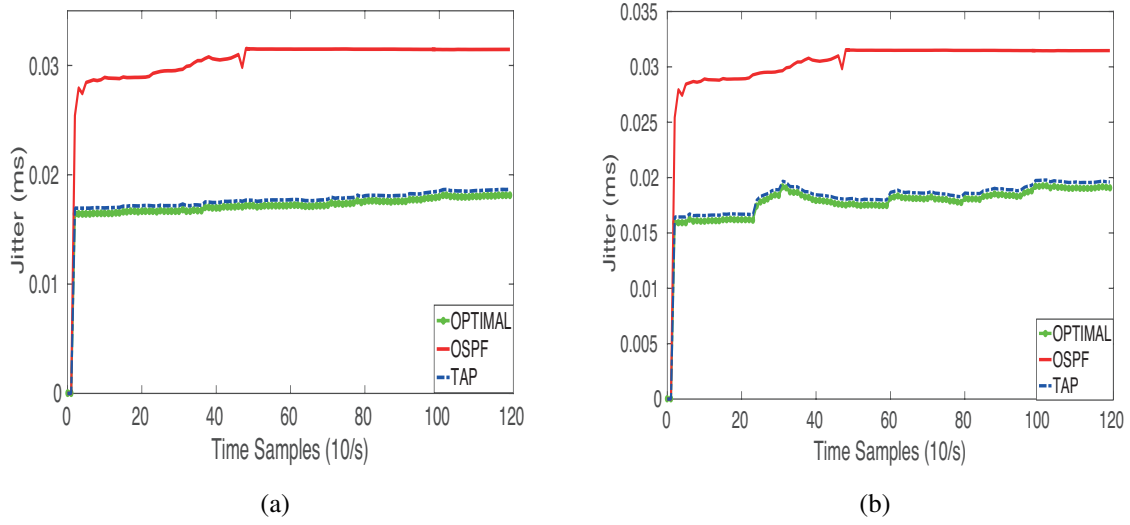
### Jitter (ms)

Jitter is a crucial QoS factor in the assessment of network performance. In the case of Tactile applications, jitter should not exceed the threshold of  $20\mu s$ . In Figure D.2, the variation in latency for a randomly chosen *Ingress-Egress* pair is measured. The same *Ingress-Egress*



**Figure D.1:** Delay (ms) for our investigated topologies (a)  $T_1M_1$  (b)  $T_1M_2$

pair was used for both of our proposed topologies. As observed in Figure D.2, the overall trend shows an increase in jitter. This is due to the larger variations of packet delay resulting from the increasing congestion in the network. Furthermore, both TAP and the optimal case perform extremely well (i.e. they never exceed the threshold of  $20\mu s$ ). Meanwhile, OSPF's jitter values are around  $30\mu s$ . To this end, OSPF's performance is reflective of its inadequacy in supporting Tactile applications. Finally, TAP performs slightly worse than the optimal scenario due to two main reasons. Firstly, the duplicate packet uses a different path compared to the original packet with a generally higher delay in the case of the former. Consequently, when the original packet has been dropped, the duplicate packet with a higher delay is considered leading to a higher variation of flows' delay. Secondly, in the optimal case, only packets belonging to Tactile class are allowed to flow through the network. To be more specific, there are no other packets belonging to other traffic classes that would add extra queueing overhead leading to higher delay variations. Therefore, the optimal case performs slightly better than TAP in terms of jitter.

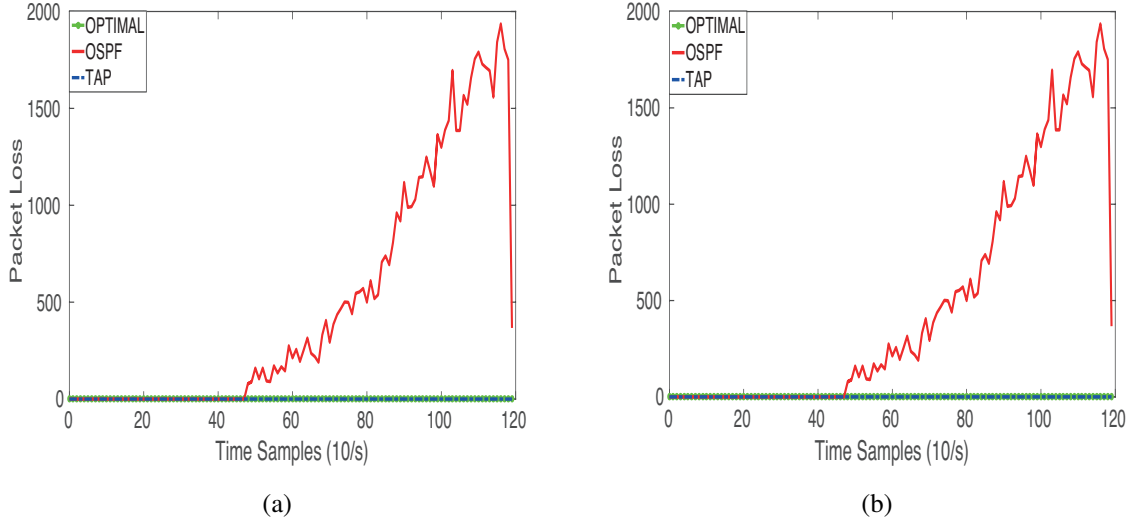


**Figure D.2:** Jitter (ms) for our investigated topologies (a)  $T_1M_1$  (b)  $T_1M_2$

### Packet Loss Rate

In the case of the Optimal scenario where only Tactile packets flow through the network, the traffic level is not so high to cause a queue overflow, hence leading to no packet loss as observed in Figure D.4. The loss rate in the case of TAP is the same as optimal. This happens due to two main reasons. Firstly, each router has two queues; one for priority packets and the other for the non-priority packets. This leads to non-priority packets not adding extra queuing delay to priority packets which would otherwise cause packet drop due to buffer overflow. Secondly, even in the case where a priority packet has been dropped, it will be restored using a duplicate packet. Namely, for the  $T_1M_1$  topology, 13 packets are restored by using the second flow and 8 for  $T_1M_2$ . More packets that belong to the first flow have been dropped in case of  $T_1M_1$  as compared with  $T_1M_2$  as  $T_1M_1$  topology has a lower meshing relative to  $T_1M_2$ ; Therefore, fewer RPs are available also as indicated in [19]. Conversely, when the congestion throughout the network is high, OSPF performs poorly making it a non viable candidate routing protocol for Tactile packets. The overall achieved loss rate of TAP for Tactile traffic was initially  $5.0839 \times 10^{-5}$  for  $T_1M_1$  and  $3.123 \times 10^{-5}$  for  $T_1M_2$ . By duplicating sessions for Tactile traffic, the loss rate for both topologies was completely eliminated.

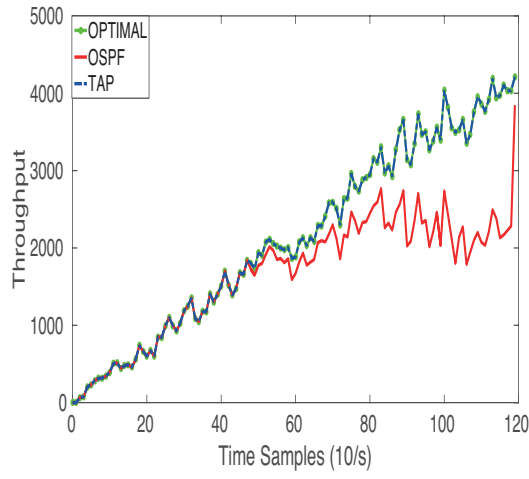




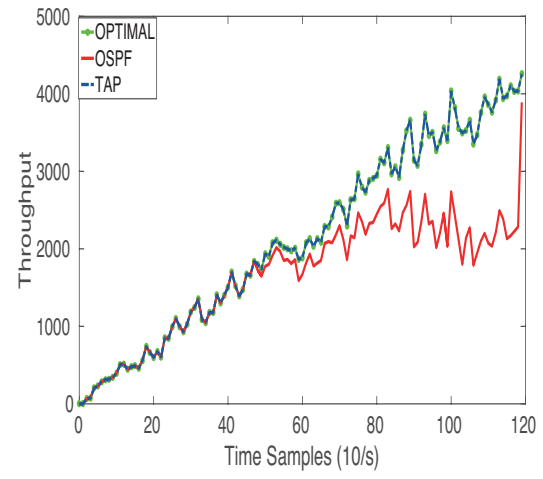
**Figure D.3:** Packet Loss for our investigated topologies (a)  $T_1M_1$  (b)  $T_1M_2$

### Throughput (packets/s)

Figure D.4 illustrates the achieved network's throughput under varying traffic classes with an increasing traffic rate injected through the network (i.e. totalling 750MB over the course of 12 seconds). As observed, the achieved throughput of TAP is similar with that of the optimal cases. This can be explained by the fact that TAP achieved the same packet loss rate as the optimal case. Meanwhile, the OSPF protocol performs poorly when the level of congestion throughout the network is high.



(a)



(b)

**Figure D.4:** Throughput (Packets/s) for our investigated topologies (a)  $T_1M_1$  (b)  $T_1M_2$

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